



U.S. DEPARTMENT OF  
**ENERGY**

Office of  
Science

**BROOKHAVEN**  
NATIONAL LABORATORY

# PERSPECTIVES ON INITIAL AND FINAL STATE CONTRIBUTIONS

TO OBSERVED AZIMUTHAL ANISOTROPIES

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June 4 2019

RHIC & AGS Annual Users' Meeting  
Brookhaven National Laboratory

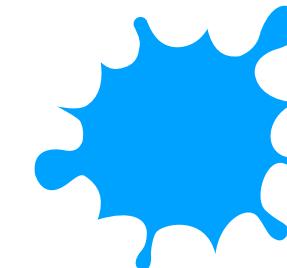
# Momentum anisotropy in heavy ion collisions

- **Discovery at RHIC:**



The Quark Gluon Plasma  
behaves like an almost perfect fluid

- **How do we know?**



**Azimuthal anisotropies in particle spectra**

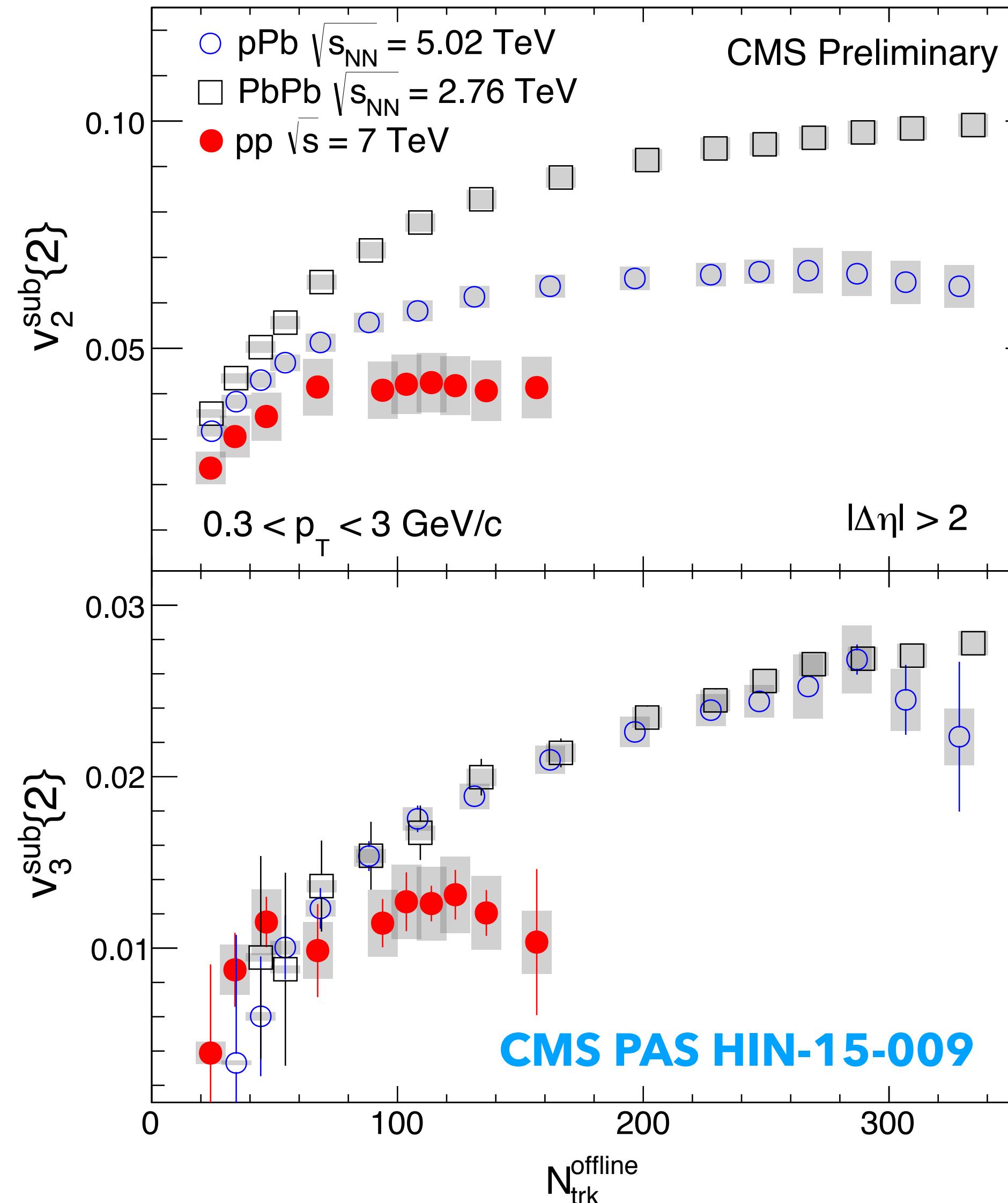
Described only if system described by hydrodynamics  
with low viscosity - system response to initial geometry

- Confirmed by results from LHC in 2010



2006

# Momentum anisotropy in small systems



see also:

**ALICE Collaboration**

Phys. Lett. B719 (2013) 29-41

Phys. Rev. C 90, 054901

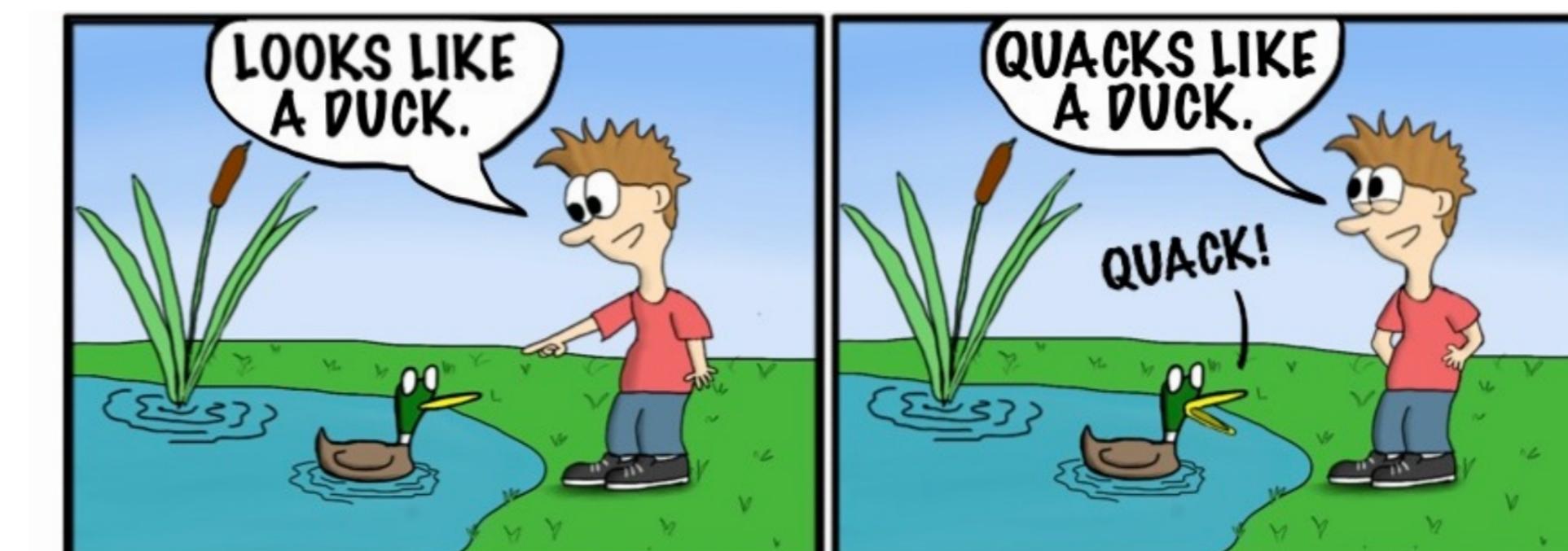
**ATLAS Collaboration**

Phys. Rev. Lett. 110, 182302 (2013);

Phys. Rev. C 90.044906 (2014)

**CMS Collaboration**

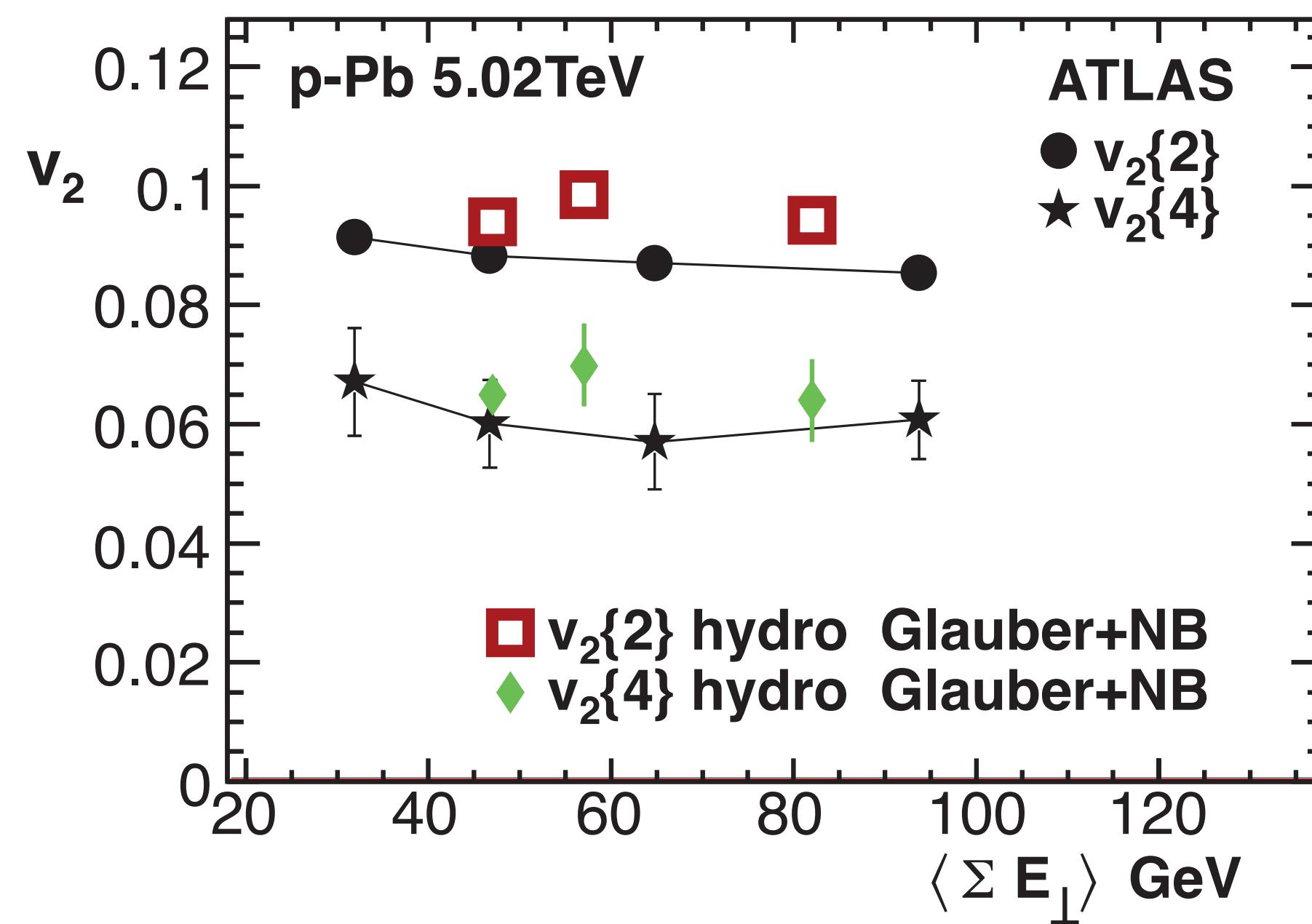
Phys.Rev.Lett. 115, 012301 (2015)



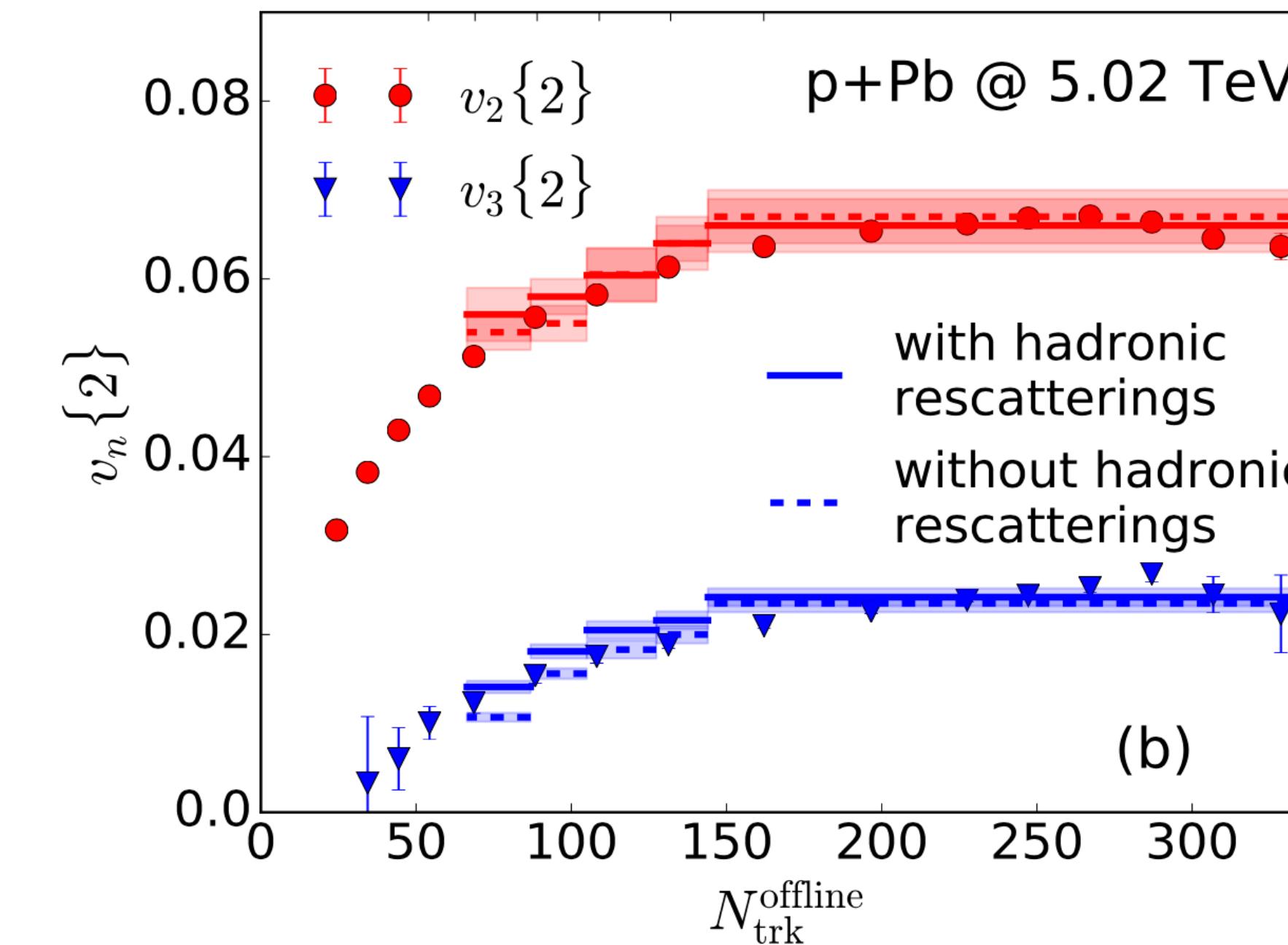
# Hydrodynamics can describe the data

Simple fluctuating initial state + hydrodynamics describes the data

ATLAS Coll. PLB725 (2013) 60-78



CMS Coll. PLB724, 213–240 (2013)



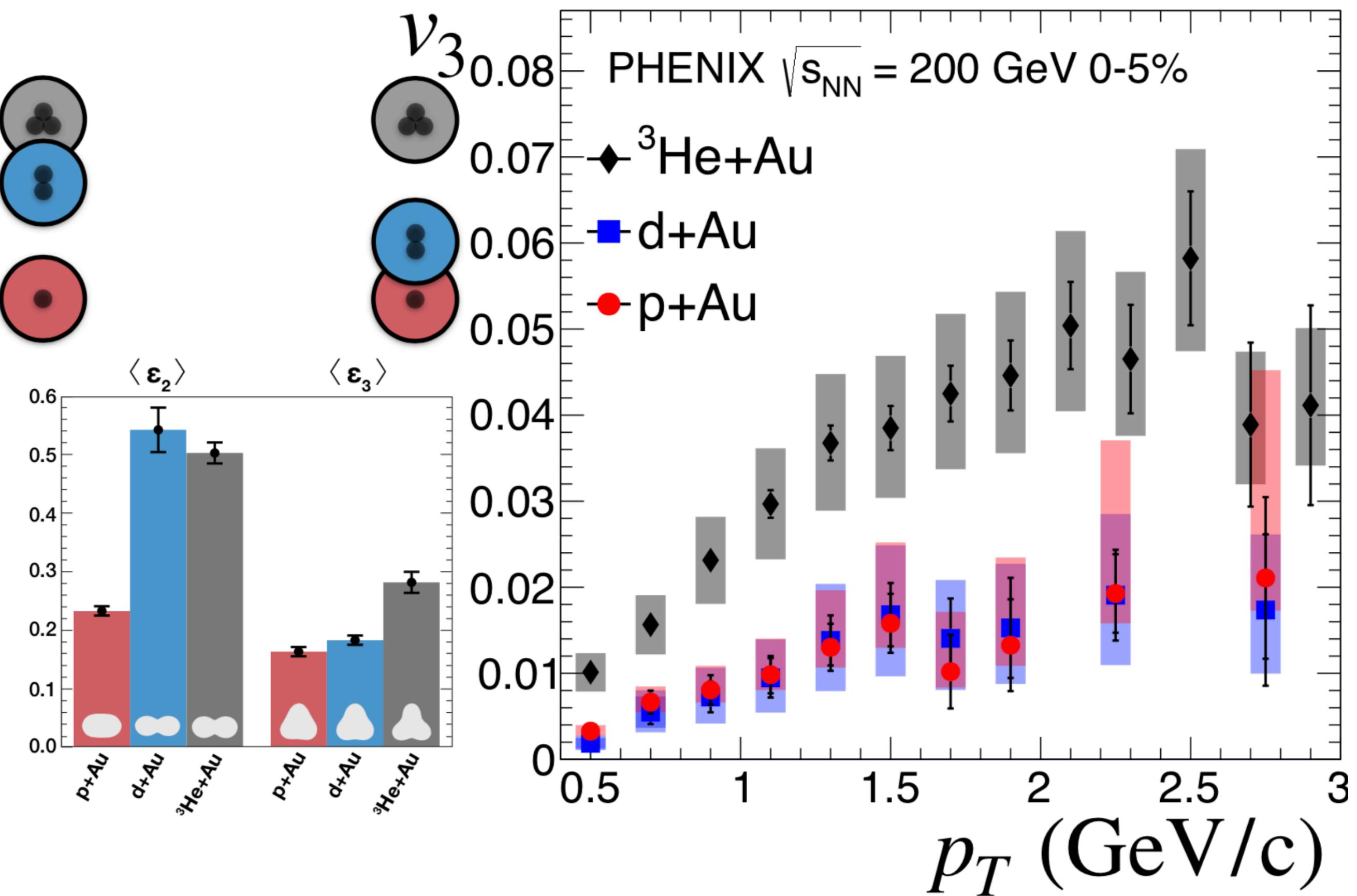
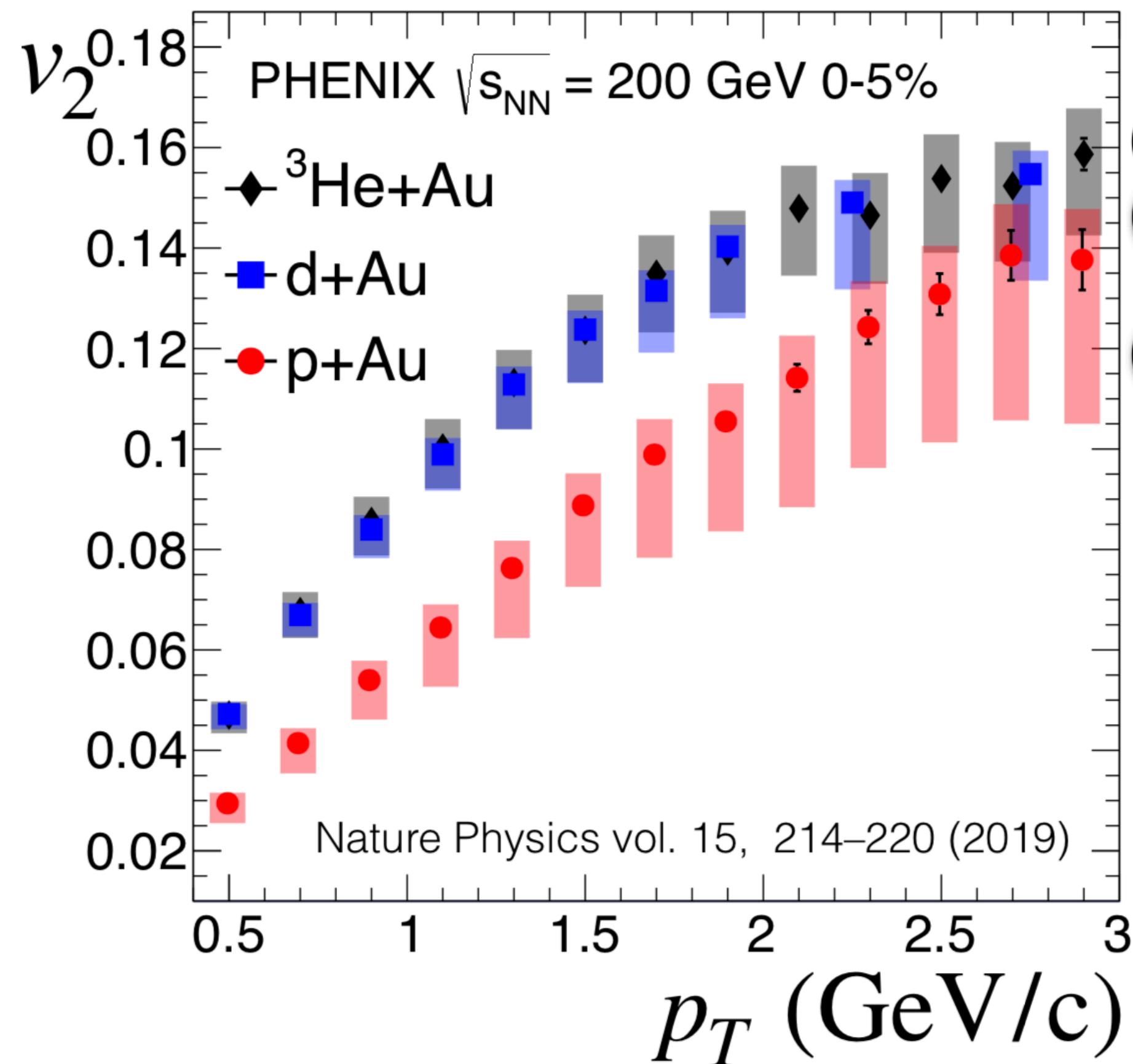
Bozek, Broniowski, PRC88 (2013) 014903

Also see: Kozlov, Luzum, Denicol, Jeon, Gale; Werner, Beicher, Guiot, Karpenko, Pierog; Romatschke; Kalaydzhyan, Shuryak, Zahed; Ghosh, Muhuri, Nayak, Varma; Qin, Mueller; Bozek, Broniowski, Torrieri; Habich, Miller, Romatschke, Xiang; T. Hirano, K. Kawaguchi, K. Murase; ...

Shen, Paquet, Denicol, Jeon, Gale, PRC95 (2017) 014906

# More evidence for geometry driven effects

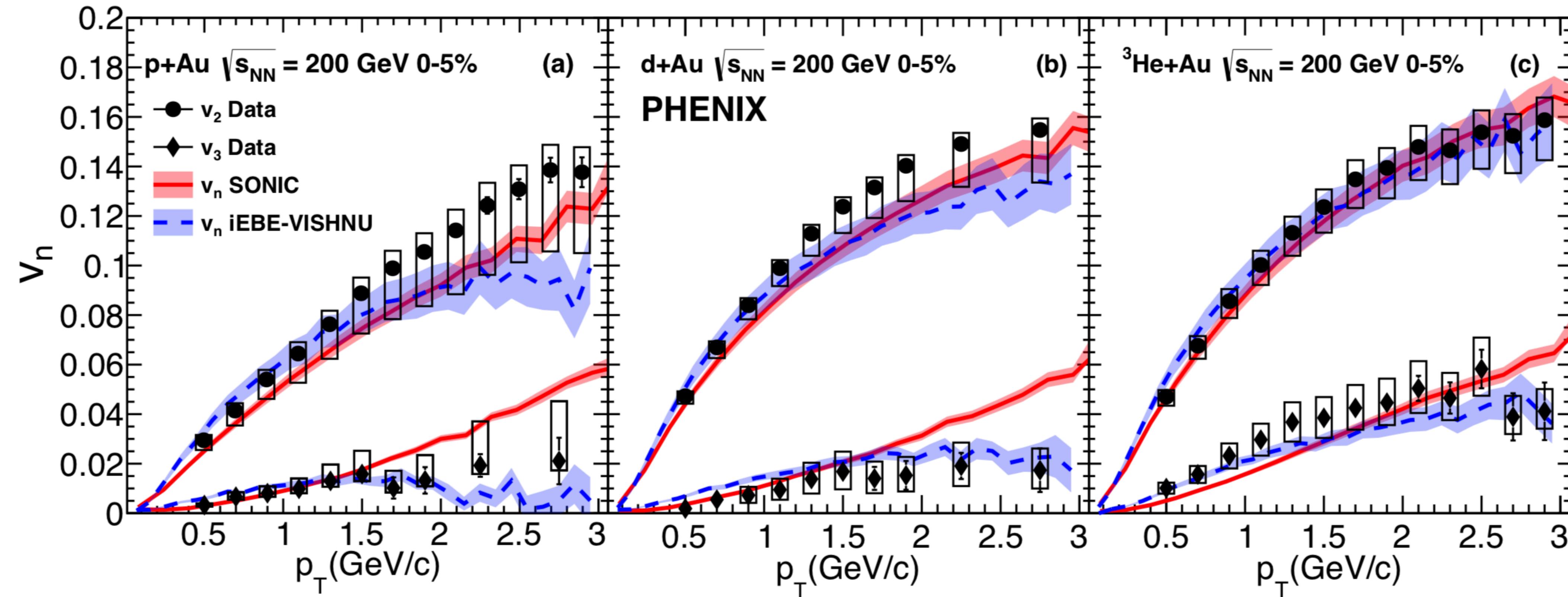
RHIC studied three different small system with different geometries



$v_n$  agree with the expectation

PHENIX Collaboration, Nature Phys. 15 (2019) no.3, 214-220

# Again, hydrodynamics can describe the data

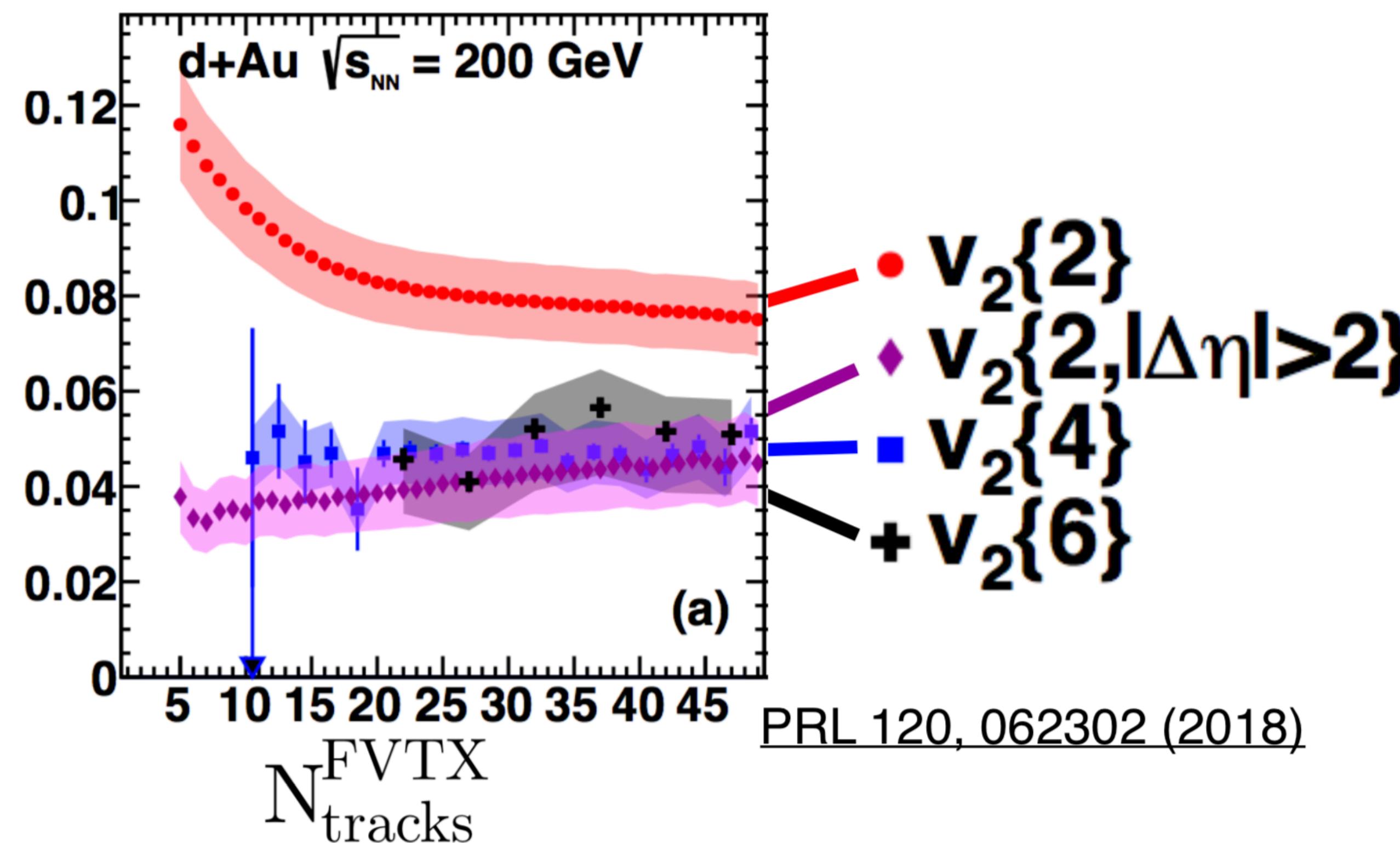


Hydrodynamic models with MC-Glauber initial conditions  
reproduce the trends

PHENIX Collaboration, Nature Phys. 15 (2019) no.3, 214-220

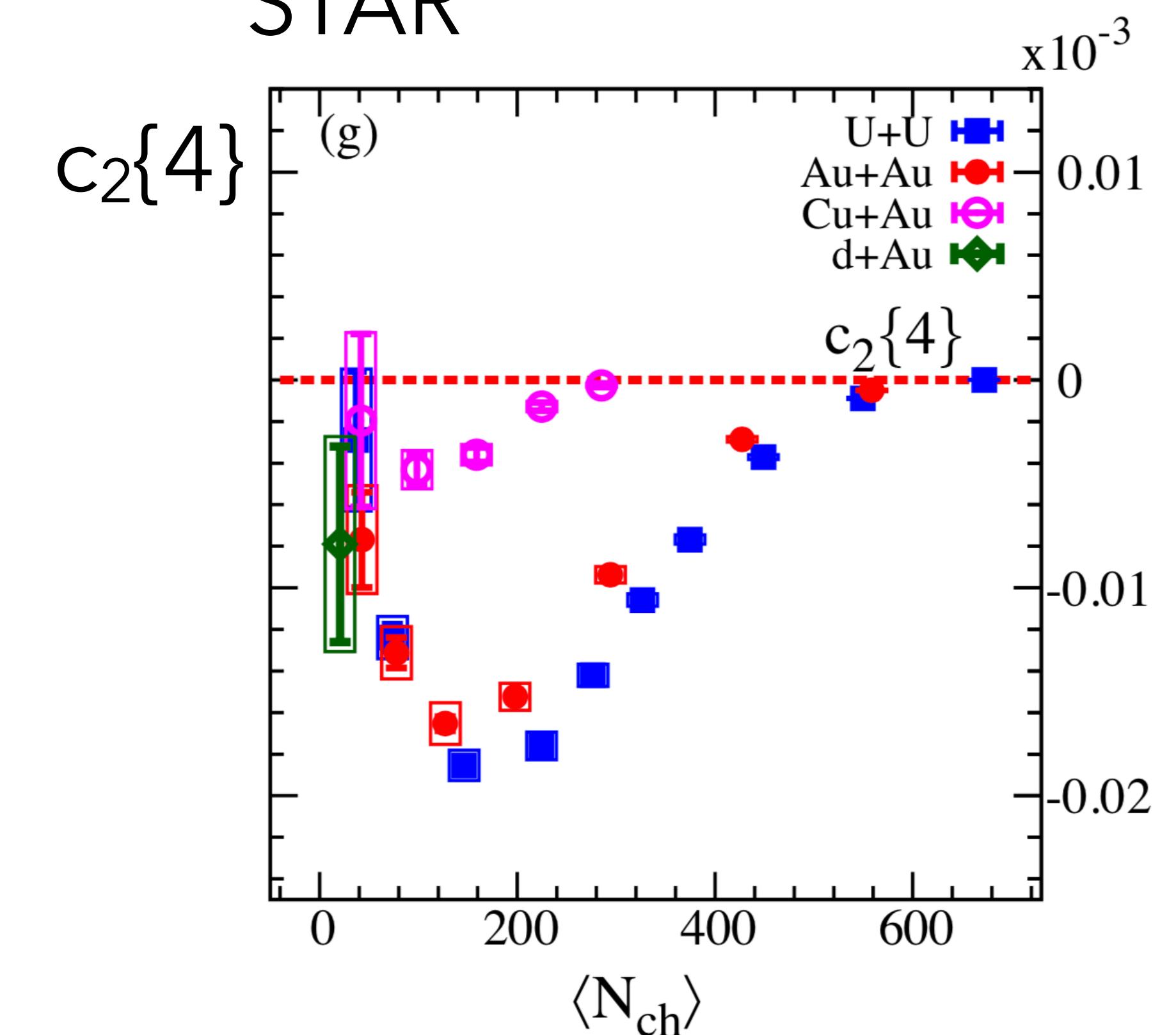
# Multi-particle correlations

PHENIX



$v_2\{4\}$  is consistent with  $v_2\{6\}$   
expected in hydro-like scenario

STAR



negative  $c_2\{4\}$  in  $d+\text{Au}$

# Hydrodynamics: Challenges

- Large viscous corrections in small systems
- Hydrodynamic fluctuations should become important
- Conversion to particles: Local conservation laws?
- Potentially large effects from (unknown) second order transport coefficients
- Initial conditions - no first principles 3 dimensional calculation of the full initial  $T^{\mu\nu}$  available as of now

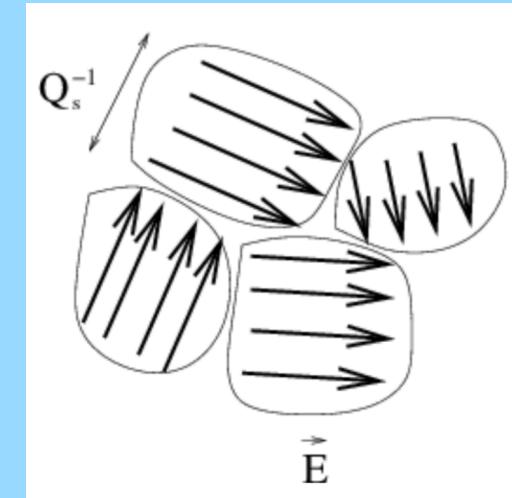
# Other sources of momentum anisotropy

# Color Glass Condensate

Sources of correlations:

Classical

Local  
anisotropy



$$1/Q_s$$

Density  
gradients

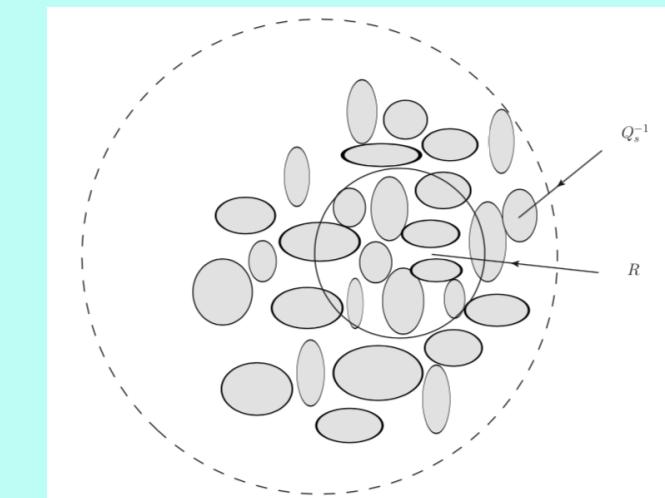
$$\frac{dQ_s}{db}/Q_s$$

Incoming gluons need to be close in the transverse plane to feel the same local structure of the target.

Quantum

Bose enhancement in  
incoming wave function

Gluonic HBT



Both come with similar contribution for enhancement of anti-aligned momenta of same magnitude (accidental?)

# Color Glass Condensate: Challenges

Odd harmonics?:

CGC expression for double inclusive production has symmetry  $(k, p) \rightarrow (k, -p)$

But this is accidental - does not survive corrections to the leading CGC approximation:

Real  $v_3$  can come from

- a) Corrections to the CGC projectile wave function:  $v_3^2 \sim a_s v_2^2$

[A. Kovner, M. Lublinsky, V. Skokov Published in Phys.Rev. D96 \(2017\) 016010](#)

- b) Going beyond the eikonal approximation

[P. Agostini, T. Altinoluk, N. Armesto arXiv:1902.04483](#)

- c) Classical final state evolution:  $v_3^2 \sim (a_s \rho)^2 v_2^2$

[B. Schenke, S. Schlichting, R. Venugopalan, Phys.Lett. B747 \(2015\) 76-82](#)

$v_4$ :

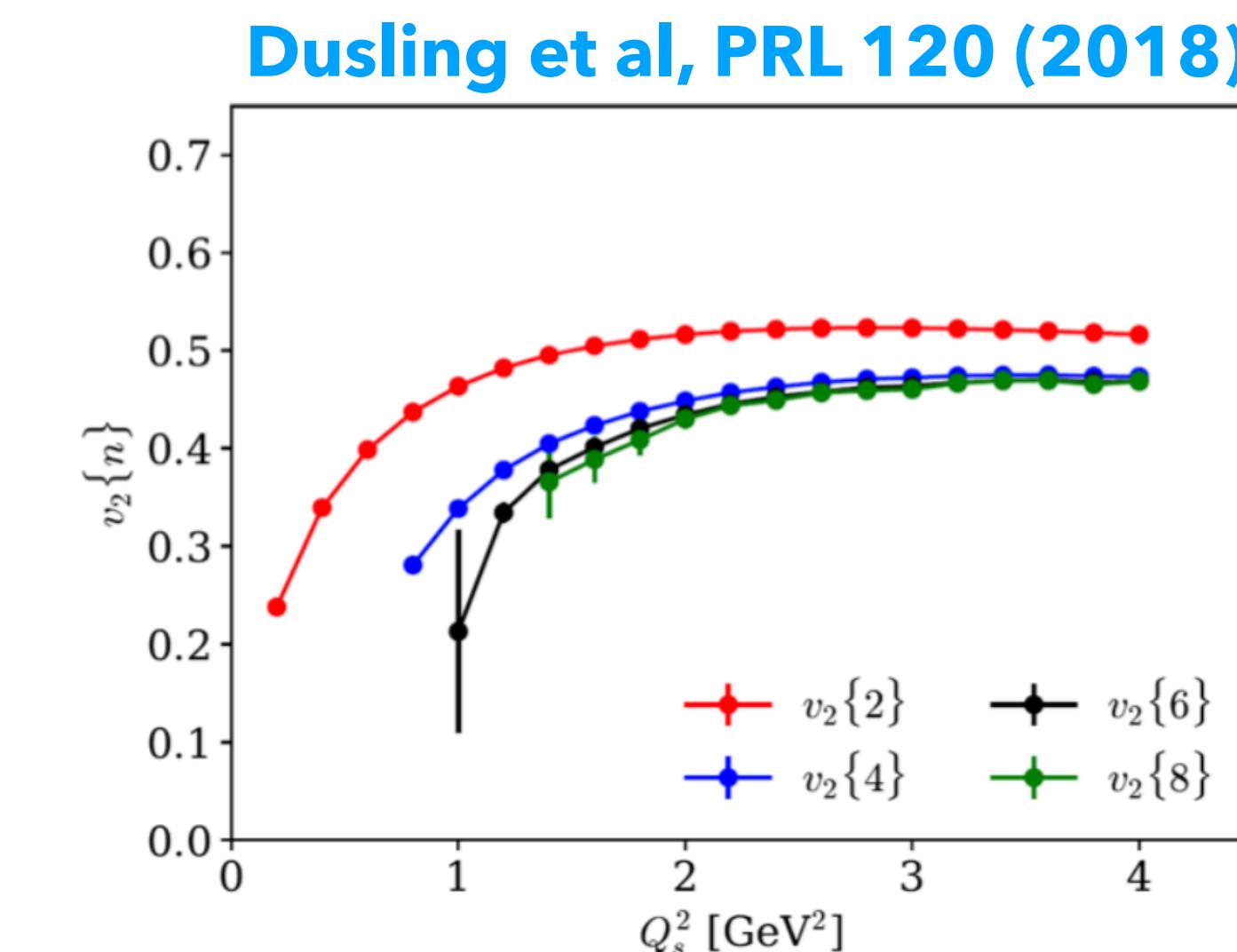
For  $|k| \approx |p| \gg Q_s$  ~sum of two  $\delta$ -functions from quantum part

Leads to  $v_4 \approx v_2$  (different from experiment)

But classical contributions different and dominant for large bin width

# CGC: Challenges

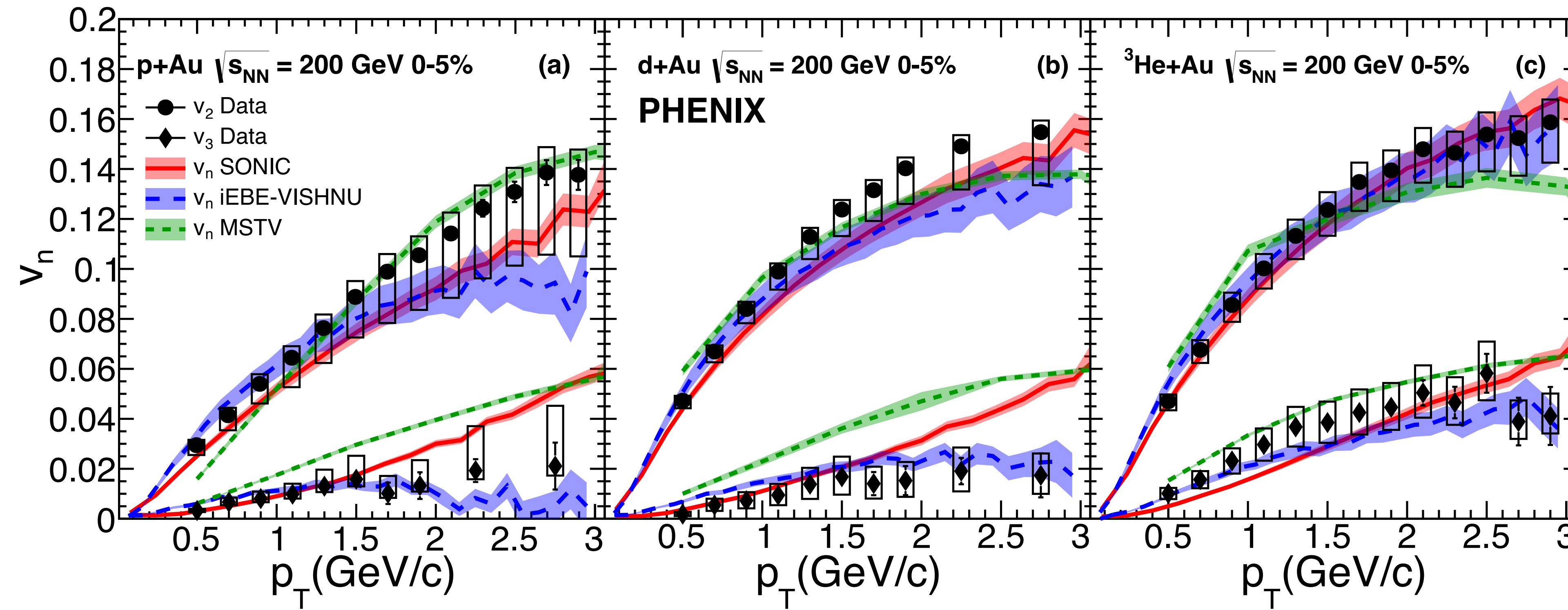
- $c_2\{4\}$ : How to get a negative  $c_2\{4\}$ ?  
Emission of  $m$  gluons from  $N$  sources with  $m > N$   
leads to such negative correlation [Blok, Wiedemann, e-Print: arXiv:1812.04113](#)
- Agreement of  $v_2\{m\}$  for  $m > 2$ . CGC has  $v_n\{m\} \sim N_c^{-2+2/m}$   
[Fukushima, Hidaka., JHEP 1711 \(2017\)](#)
- Hadronization
- Final state evolution
- Projectile wave function  
(MV model not so good for small projectile)



$$N_c = 1$$

# CGC: Correction

PHENIX Collaboration, Nature Phys. 15 (2019) no.3, 214-220



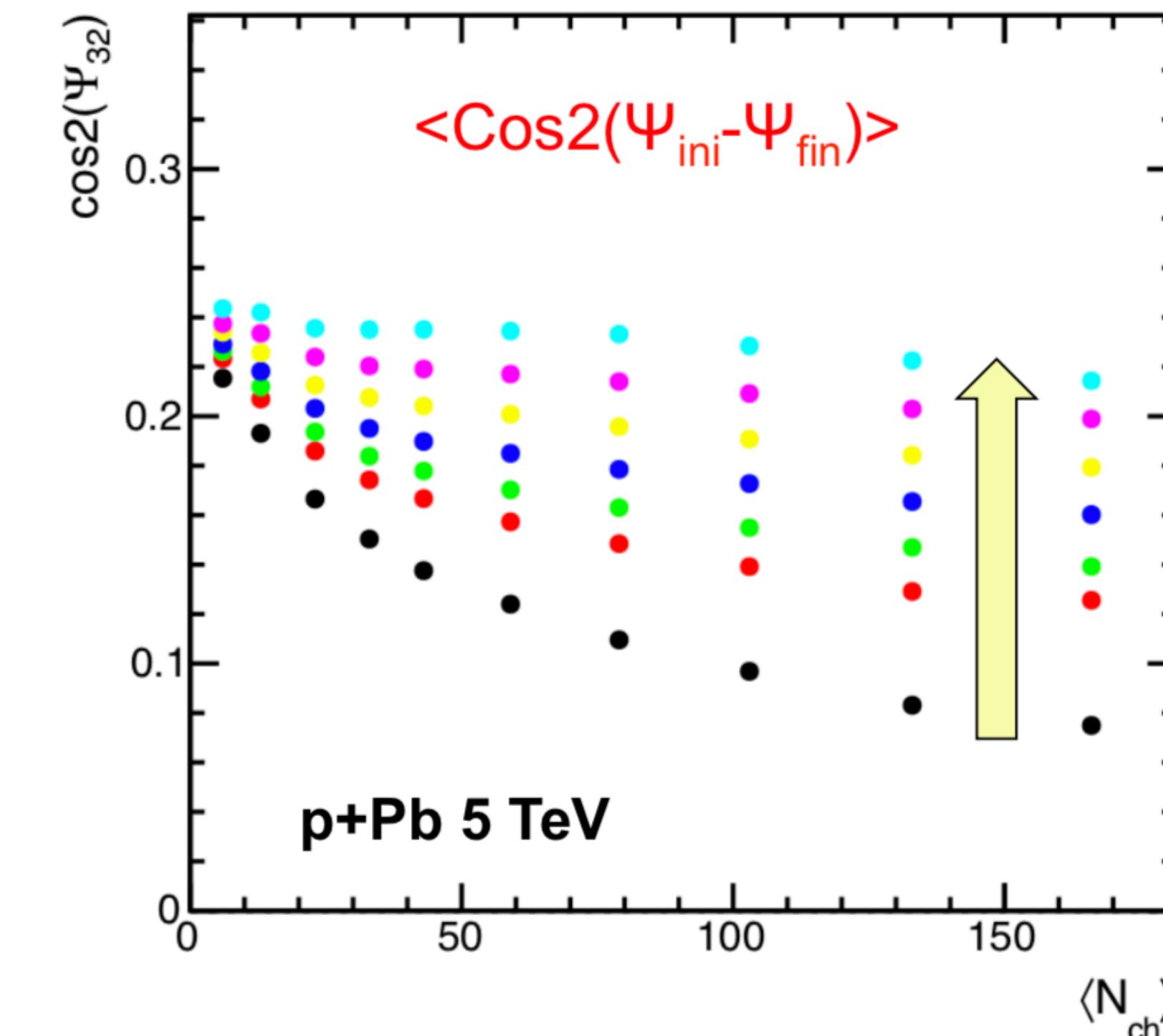
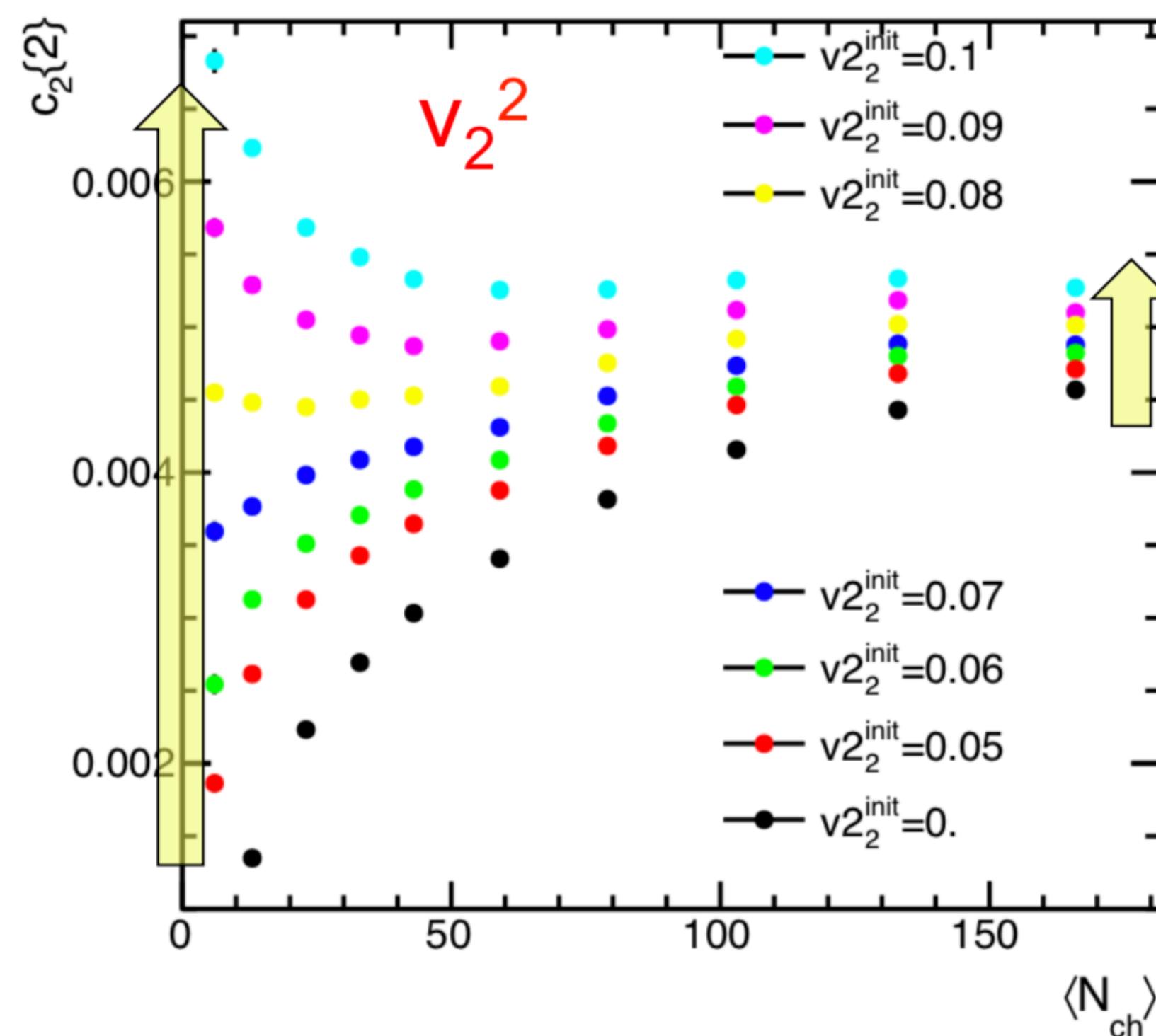
MSTV: Mace, Skokov, Tribedy, Venugopalan, Phys.Rev.Lett. 121 (2018) no.5, 052301

Green curve is not correct - scale on the  $p_T$ -axis is off by a factor  $\sim 5$  ( $1/(\hbar c)$ )

Erratum to appear

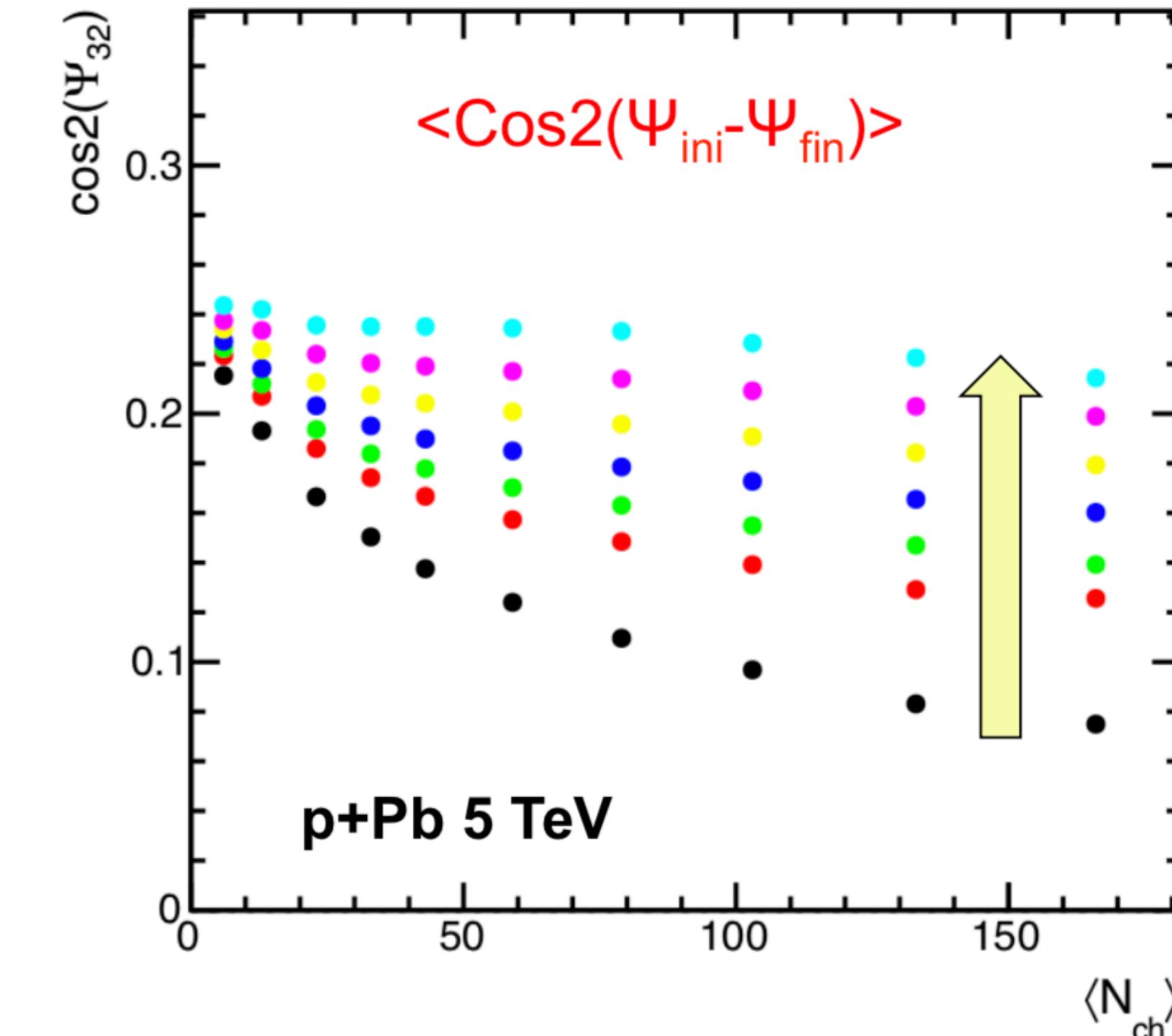
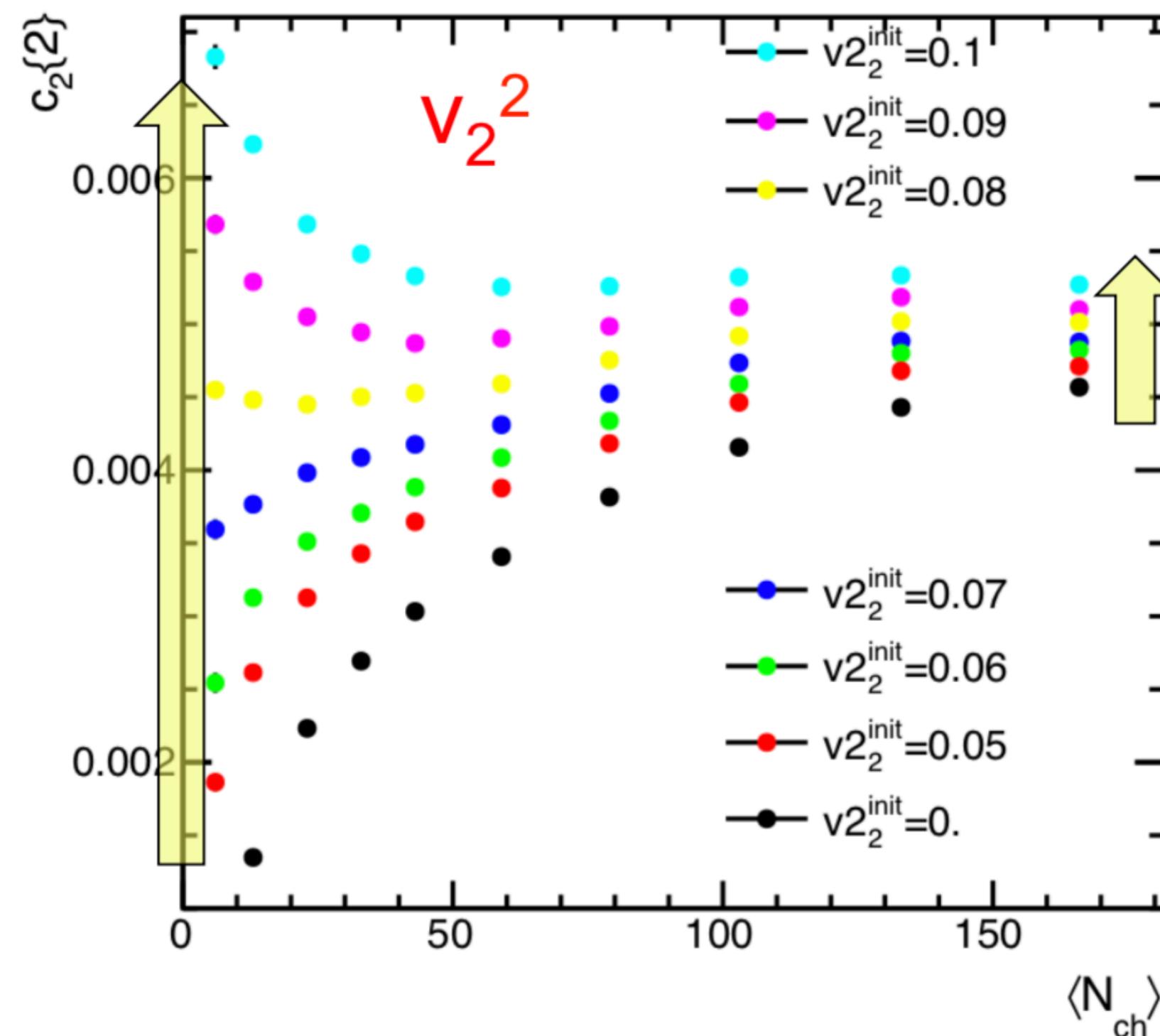
# Combining initial + final state contributions

- AMPT; Randomize particle directions; Impose initial momentum anisotropy
- Perform final state evolution
- Study effect of initial anisotropy on final  $v_2$  and event plane angle



# Combining initial + final state contributions

- Low  $N_{ch}$  : Final flow  $\approx$  Initial flow expected for free streaming
- High  $N_{ch}$ : Final flow increases slowly with initial flow.
- The final flow is biased toward the direction of the initial flow.



Initial flow could survive and bias the geometry-driven flow (in AMPT)

# Combining initial + final state contributions

IP-Glasma + MUSIC + UrQMD

- IP-Glasma contains initial state momentum anisotropy  
(largely uncorrelated with global geometry)
- We feed the IP-Glasma  $T^{\mu\nu}$  into hydrodynamics  
Initial anisotropy encoded in initial flow profile and shear stress tensor  
EOS changes at switching: Can absorb difference in initial bulk pressure  $\Pi$
- Hydrodynamic evolution will generate anisotropy in response to geometry

Which will dominate the final observables?

# Combining initial + final state contributions

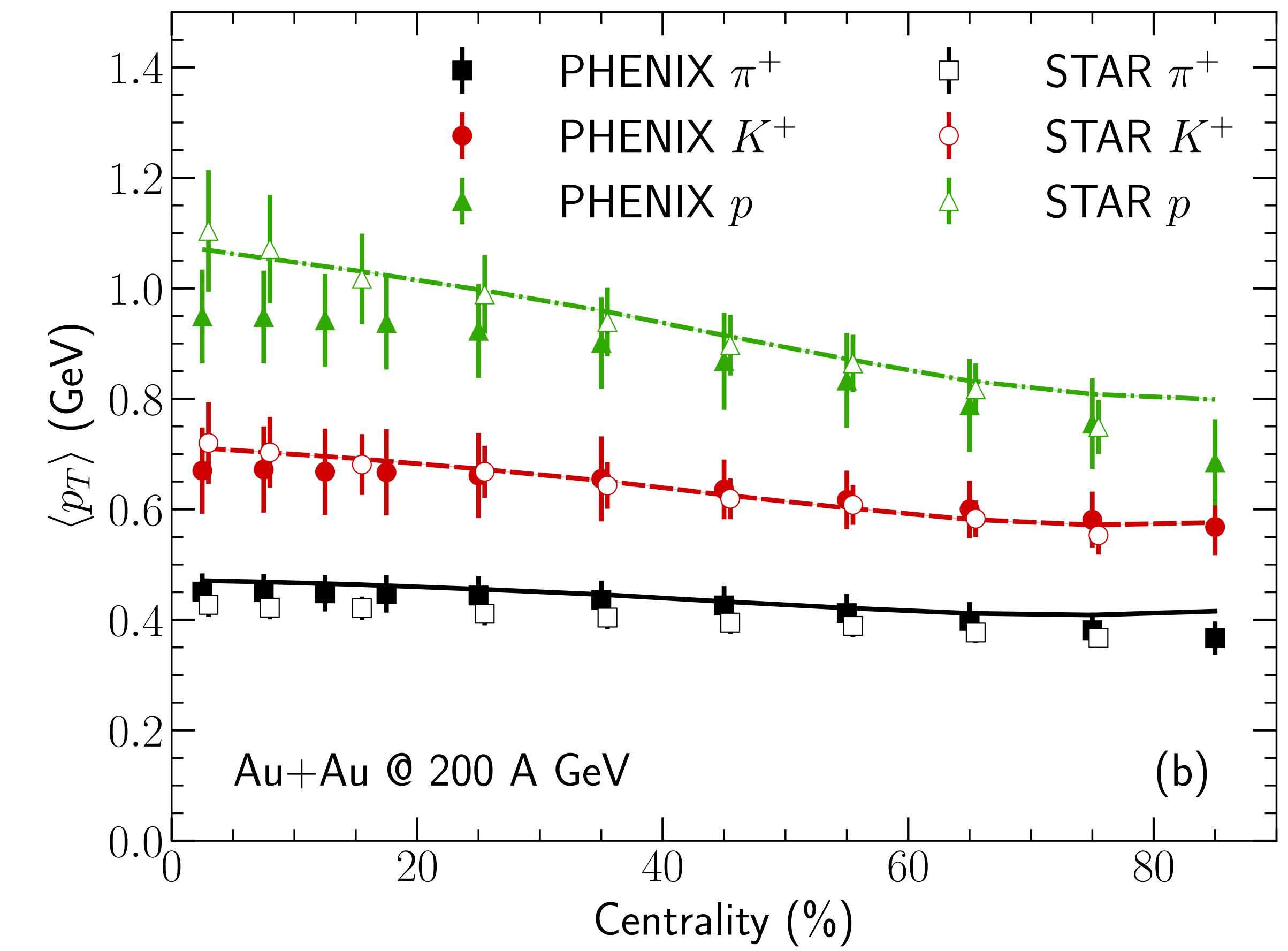
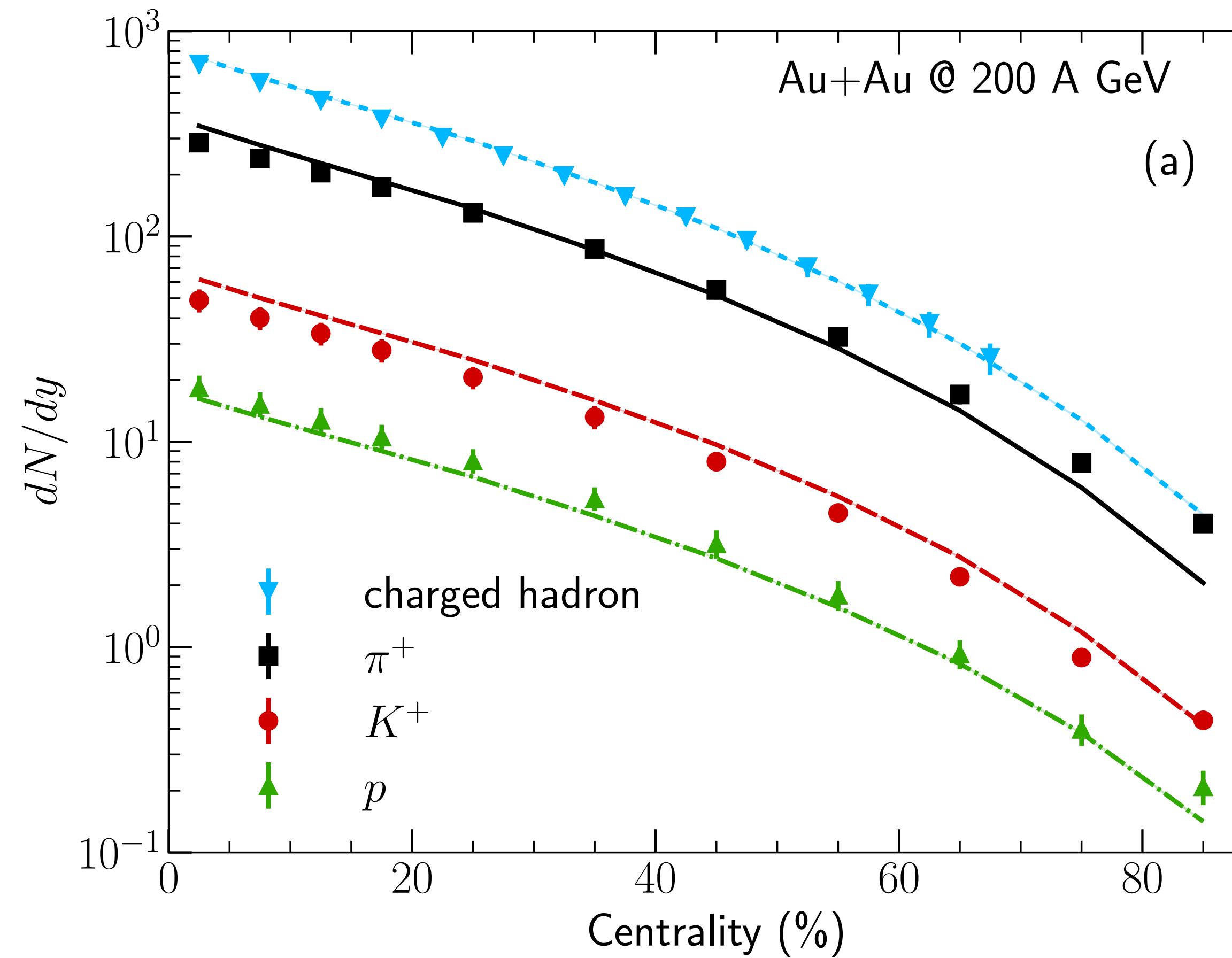
IP-Glasma + MUSIC + UrQMD

- Sample particles on the switching surface  
(surface of constant energy density) according to Cooper-Frye formula
- Feed particles to UrQMD  
S. A. Bass et al., Prog. Part. Nucl. Phys. 41, 255-369 (1998)  
M. Bleicher et al., J. Phys. G25, 1859-1896 (1999)  
which performs resonance decays and scatterings

Local conservation laws should be fulfilled when converting to particles  
currently they are not (assume grand canonical system in every cell)

# Constrain all parameters in Au+Au collisions

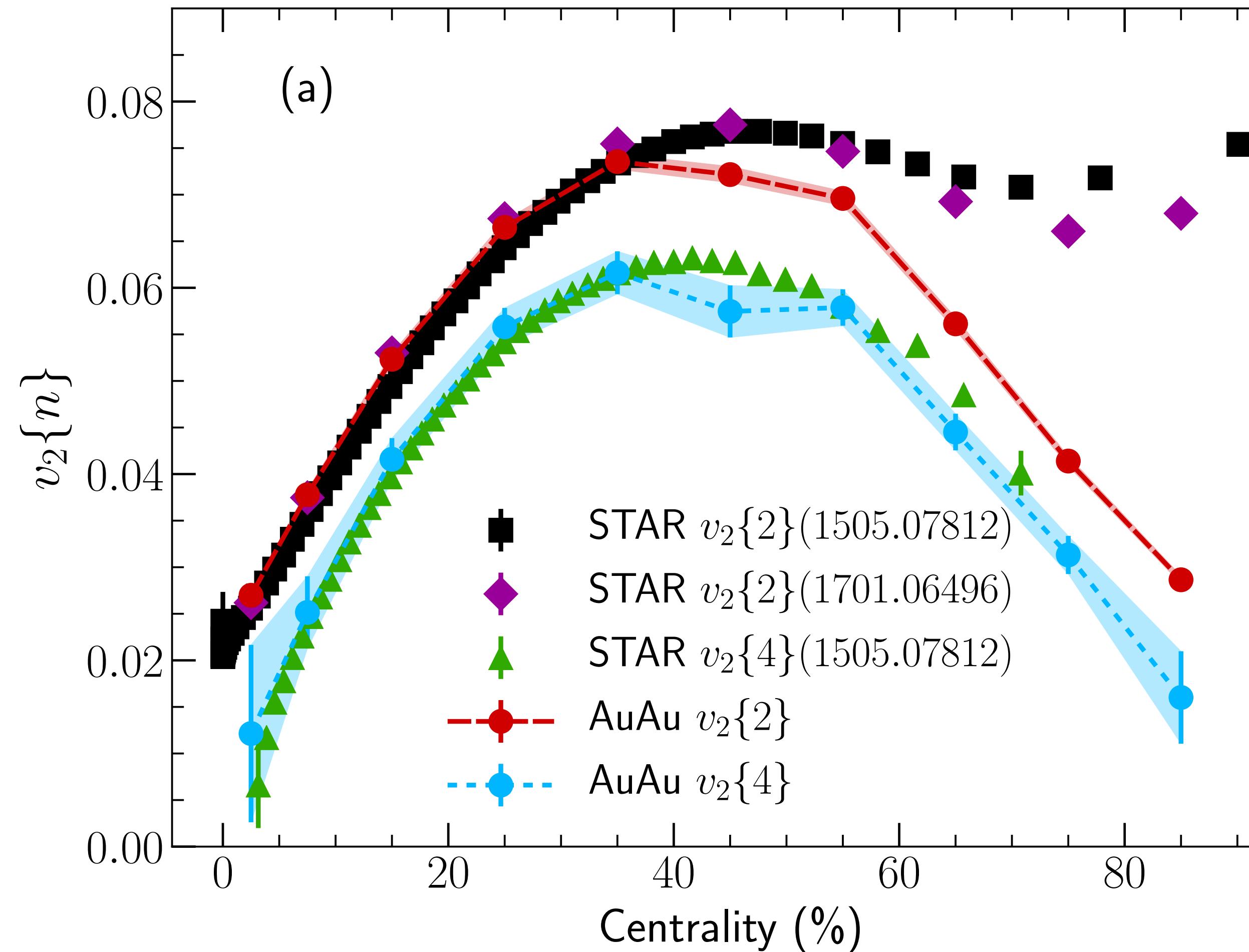
IP-Glasma + MUSIC + UrQMD [Schenke, Shen, Tribedy, Phys.Rev. C99 \(2019\) 044908](#)



Experimental data: PHENIX Collaboration, Phys. Rev. C 69, 034909 (2004); STAR Collaboration, Phys. Rev. C 79, 034909 (2009)

# Constrain all parameters in Au+Au collisions

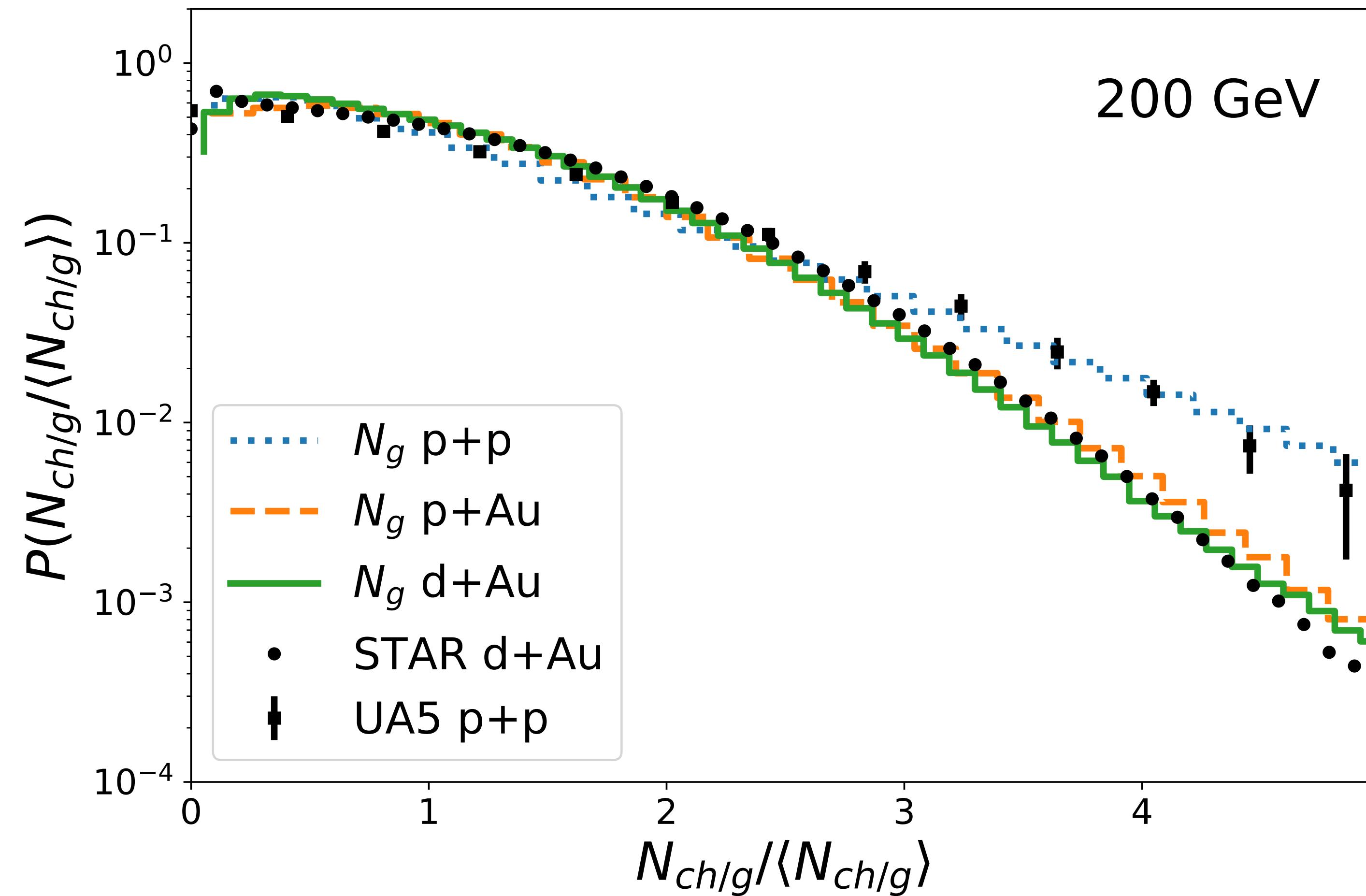
IP-Glasma + MUSIC + UrQMD [Schenke, Shen, Tribedy, Phys.Rev. C99 \(2019\) 044908](#)



Experimental data: STAR Collaboration,  
Phys. Rev. Lett. 115, 222301 (2015);  
Phys. Rev. C 98, 034918 (2018)

# Small systems: I. Multiplicity distributions

IP-Glasma (+ MUSIC + UrQMD) **Schenke, Shen, Tribedy, in preparation**



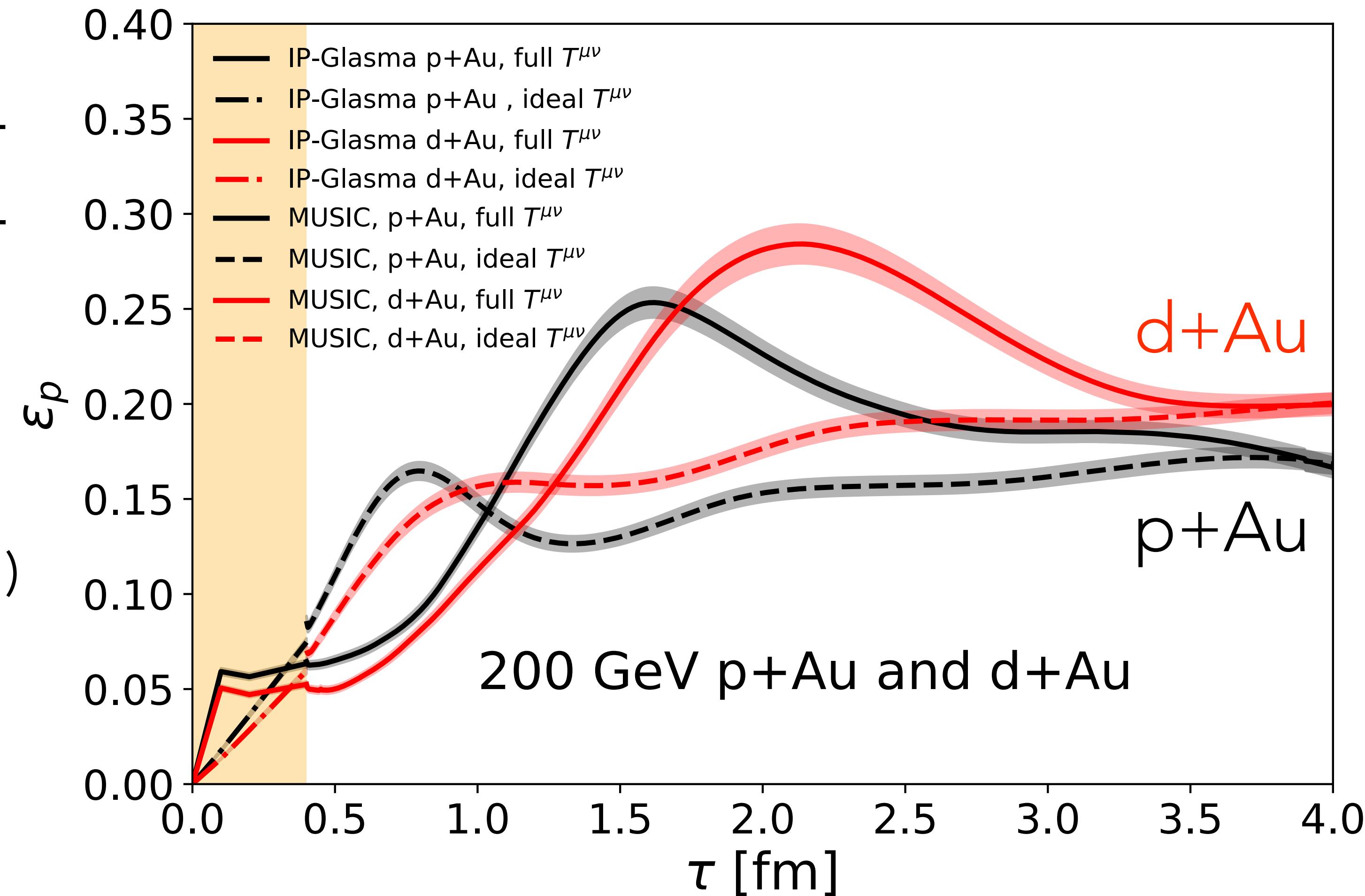
# Small systems: II. Momentum anisotropy evolution

IP-Glasma + MUSIC (+ UrQMD) **Schenke, Shen, Tribedy, in preparation**

$$\epsilon_p = \sqrt{\frac{\langle T^{xx} - T^{yy} \rangle^2 + \langle 2T^{xy} \rangle^2}{\langle T^{xx} + T^{yy} \rangle^2}}$$

using

- ideal part of  $T^{\mu\nu}$  only (dashed)
- full  $T^{\mu\nu}$  (solid)

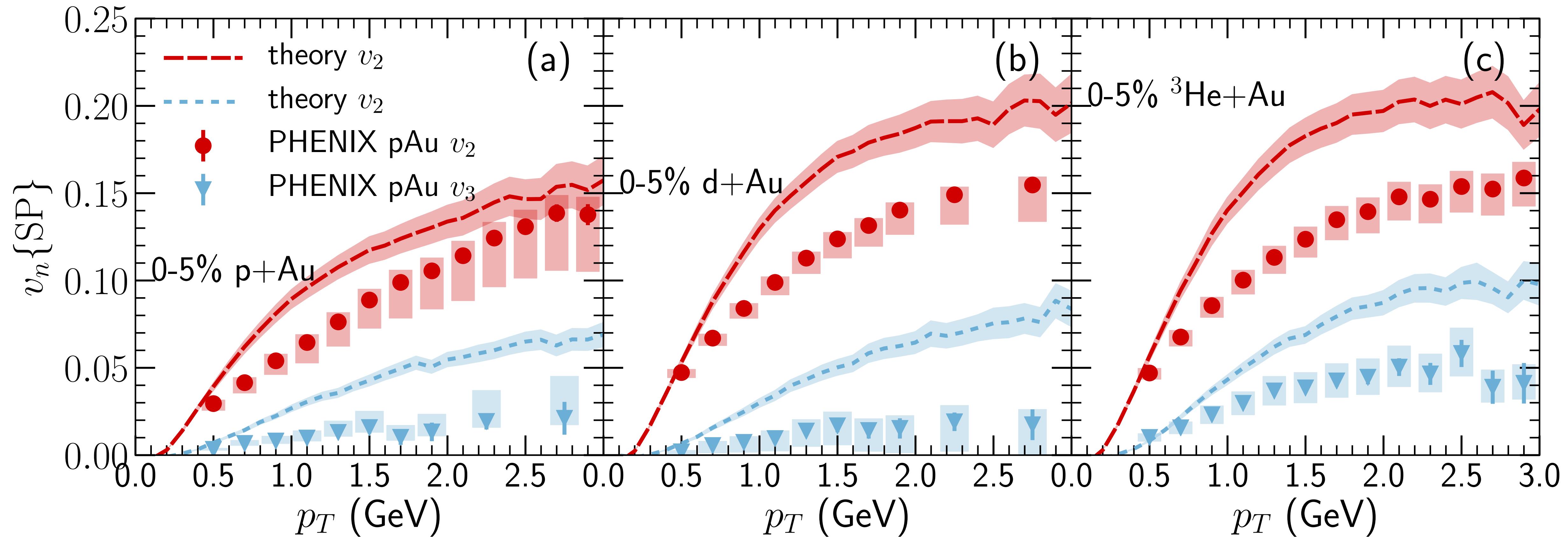


# Small systems: III. Anisotropy coefficients

IP-Glasma + MUSIC + UrQMD

Schenke, Shen, Tribedy, in preparation

PHENIX Collaboration, Nature Phys. 15 (2019), 214-220



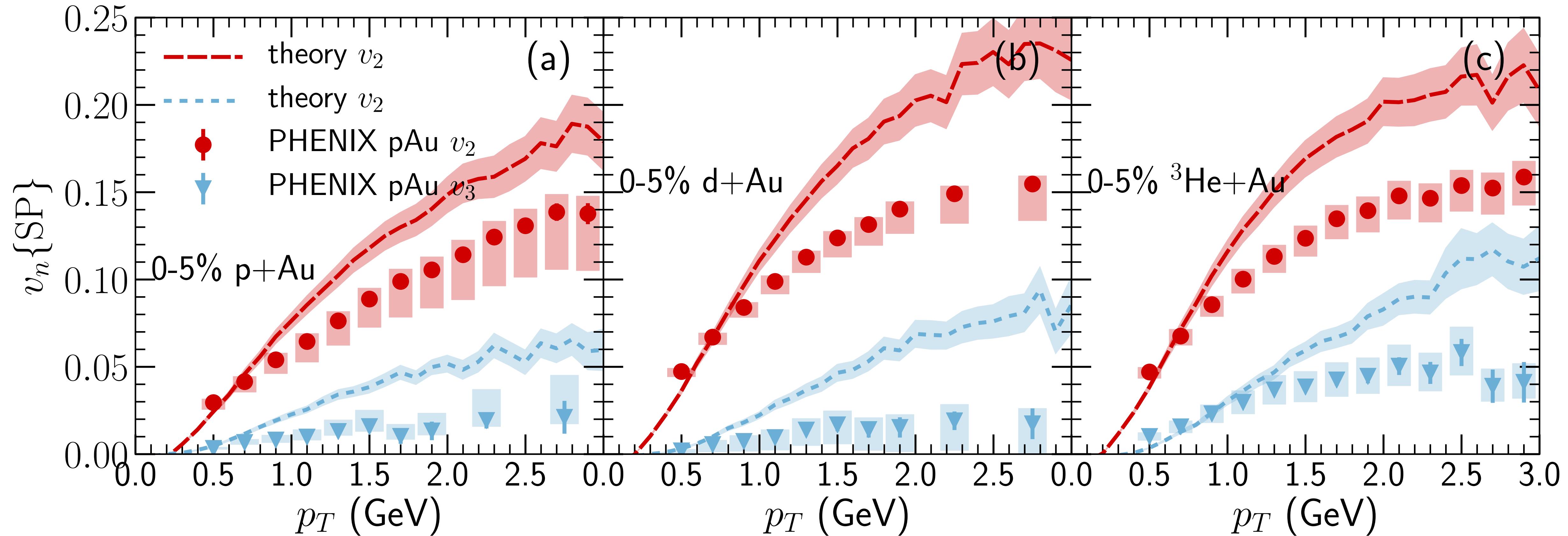
Calculation:  $dN/d\eta = 19.6$  for dAu, 11.3 for pAu

# Small systems: III. Anisotropy coefficients

IP-Glasma + MUSIC + UrQMD

Schenke, Shen, Tribedy, in preparation

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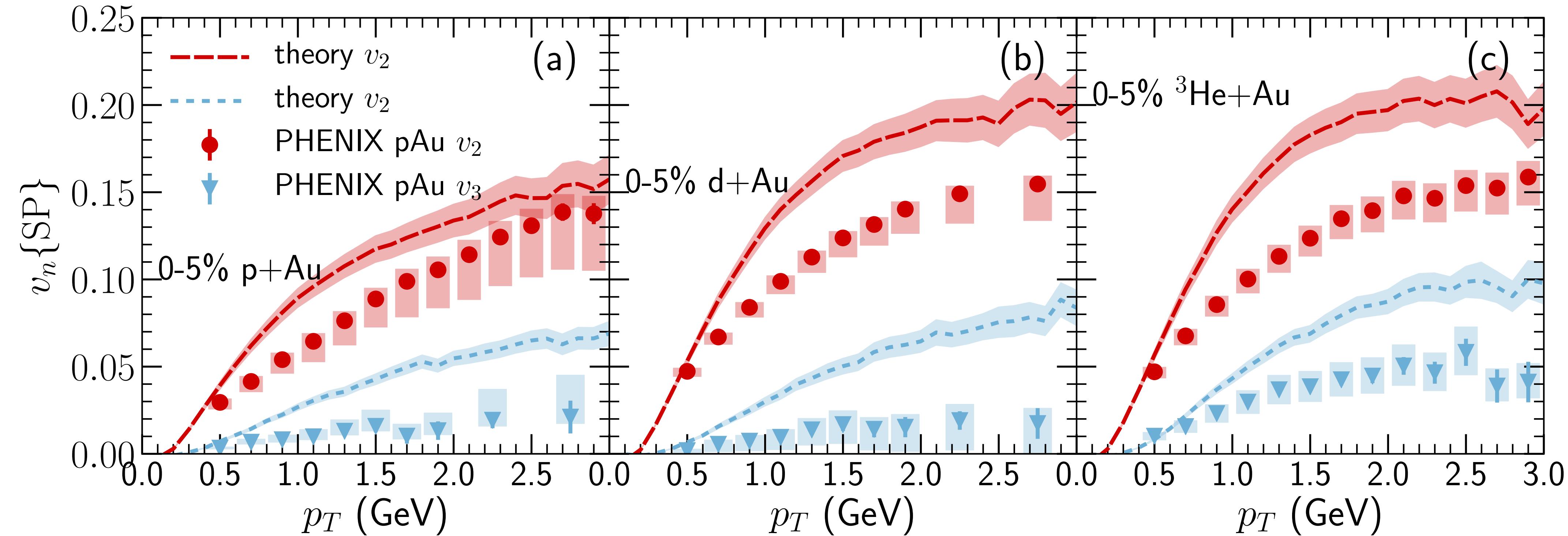
No initial  $\Pi$

# Small systems: III. Anisotropy coefficients

IP-Glasma + MUSIC + UrQMD

Schenke, Shen, Tribedy, in preparation

PHENIX Collaboration, Nature Phys. 15 (2019), 214-220



Data has large  $\Delta\eta$ -gap. Calculation is boost invariant.

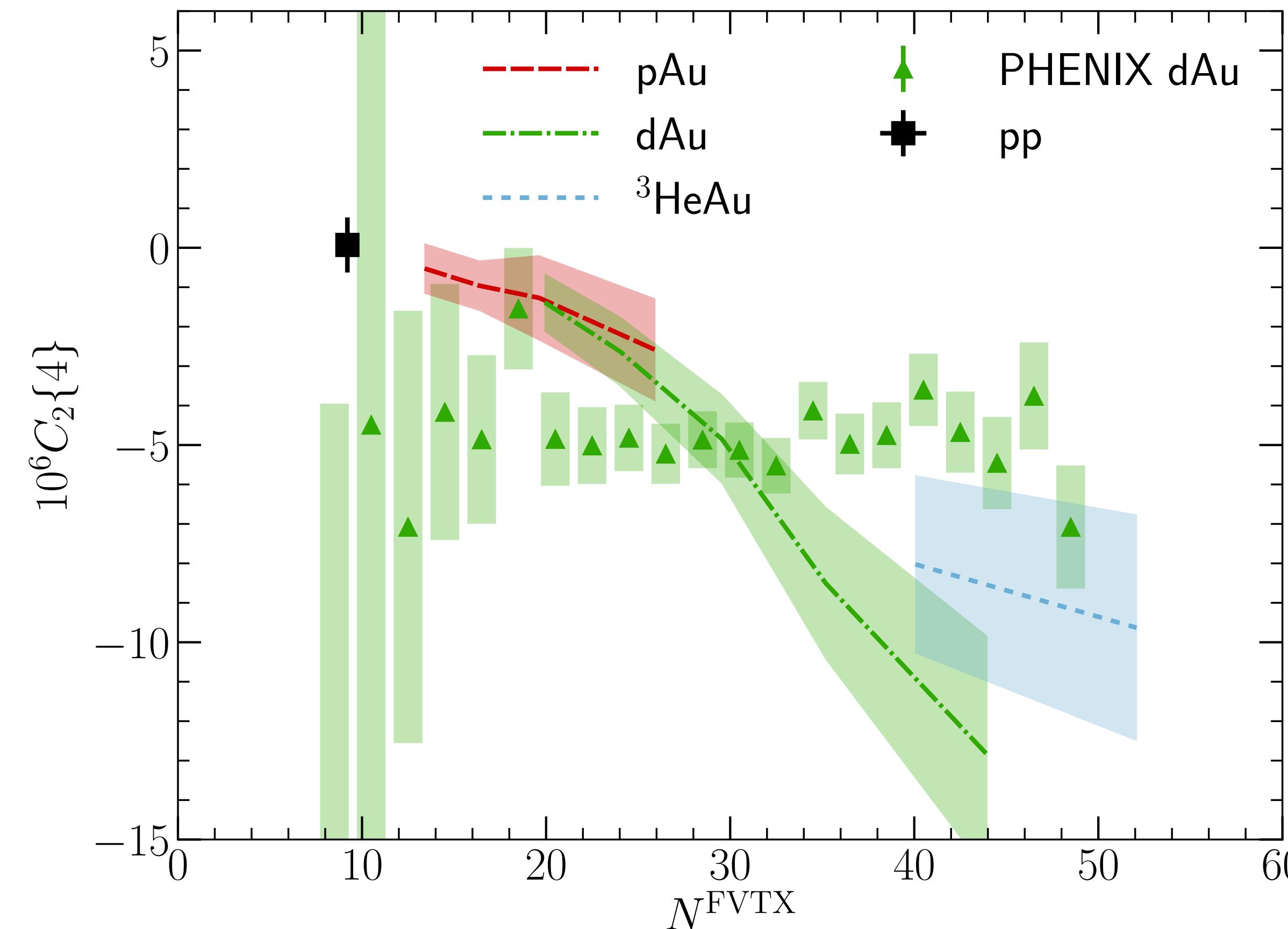
From LHC we know longitudinal decorrelation could decrease  $v_n$  20-30%

# Small systems: 4-particle correlations

IP-Glasma + MUSIC + UrQMD

Schenke, Shen, Tribedy, in preparation

PHENIX Collaboration, Phys. Rev. Lett. 120 (2018) 062302



dAu close to PHENIX data but  
stronger multiplicity dependence

Both pAu and dAu have  
**negative  $\mathbf{c}_2\{4\}$**   
(PHENIX result positive in pAu)

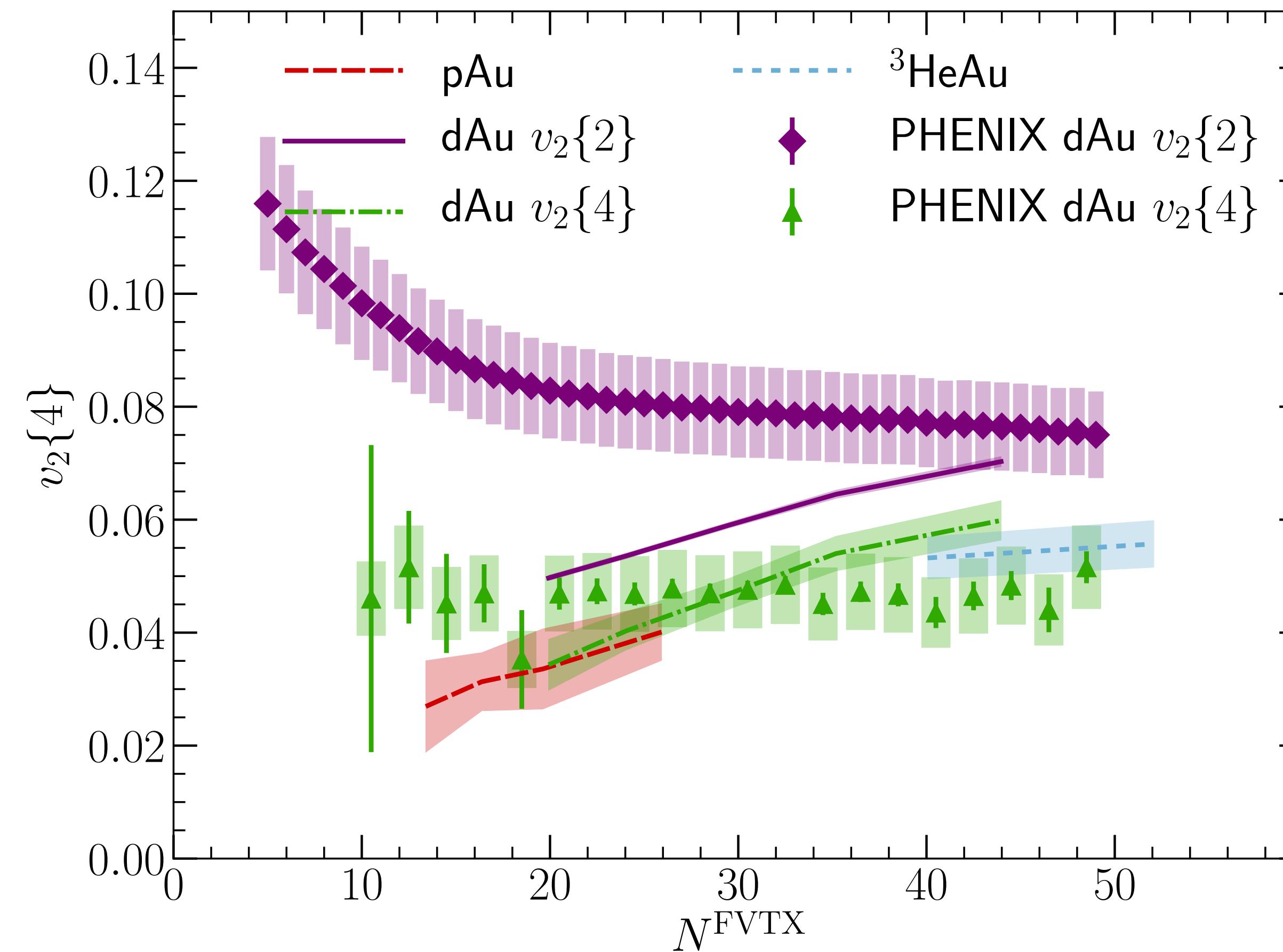
pp needs more statistics

# Small systems: 2- and 4-particle correlations

IP-Glasma + MUSIC + UrQMD

Schenke, Shen, Tribedy, in preparation

PHENIX Collaboration, Phys. Rev. Lett. 120 (2018) 062302



boxes: systematic error  
bars: statistical error

# Small systems: Details matter

IP-Glasma + MUSIC + UrQMD [Schenke, Shen, Tribedy, in preparation](#)

Sensitivity to:

- initial flow and shear tensor
- presence/values of second order transport coefficients
- type of matching of Yang-Mills EoS (IP-Glasma) to lattice EOS (hydro)
- switching time

Potentially important:

- hydrodynamic fluctuations
- local charge (momentum) conservation when sampling particles
- prescription for off-equilibrium particle distributions
- ...

# Summary

- Small systems show similar momentum anisotropies as large ones
- Initial momentum distributions are anisotropic  
(classical and quantum effects)
- Systematics of observed anisotropies seem to follow system geometry
- Purely initial state models have trouble describing all systematics
- Hints at presence of strong final state interactions
- Role of initial state may still not be negligible

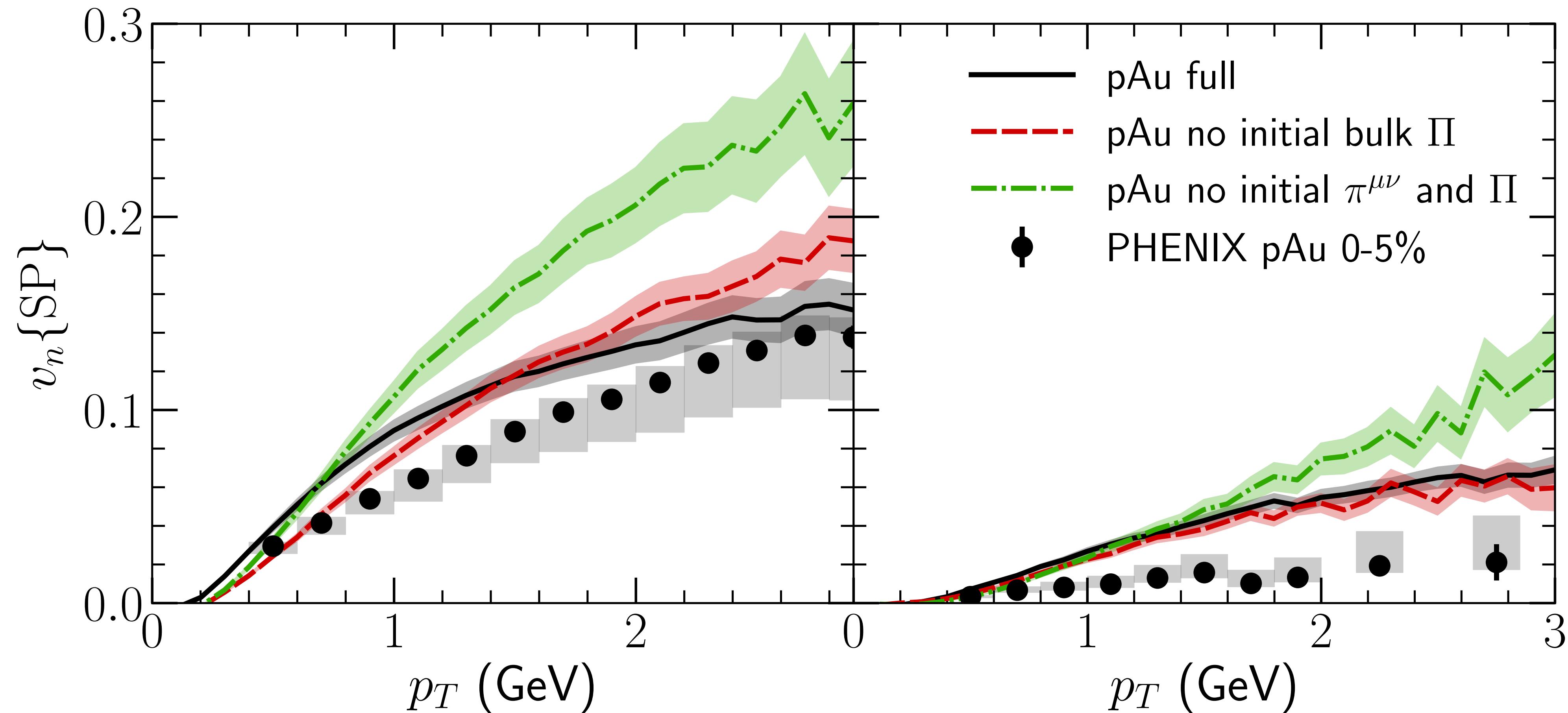
# BACKUP

# Small systems: 4-particle correlations

IP-Glasma + MUSIC + UrQMD

Schenke, Shen, Tribedy, in preparation

PHENIX Collaboration, Phys. Rev. Lett. 120 (2018) 062302

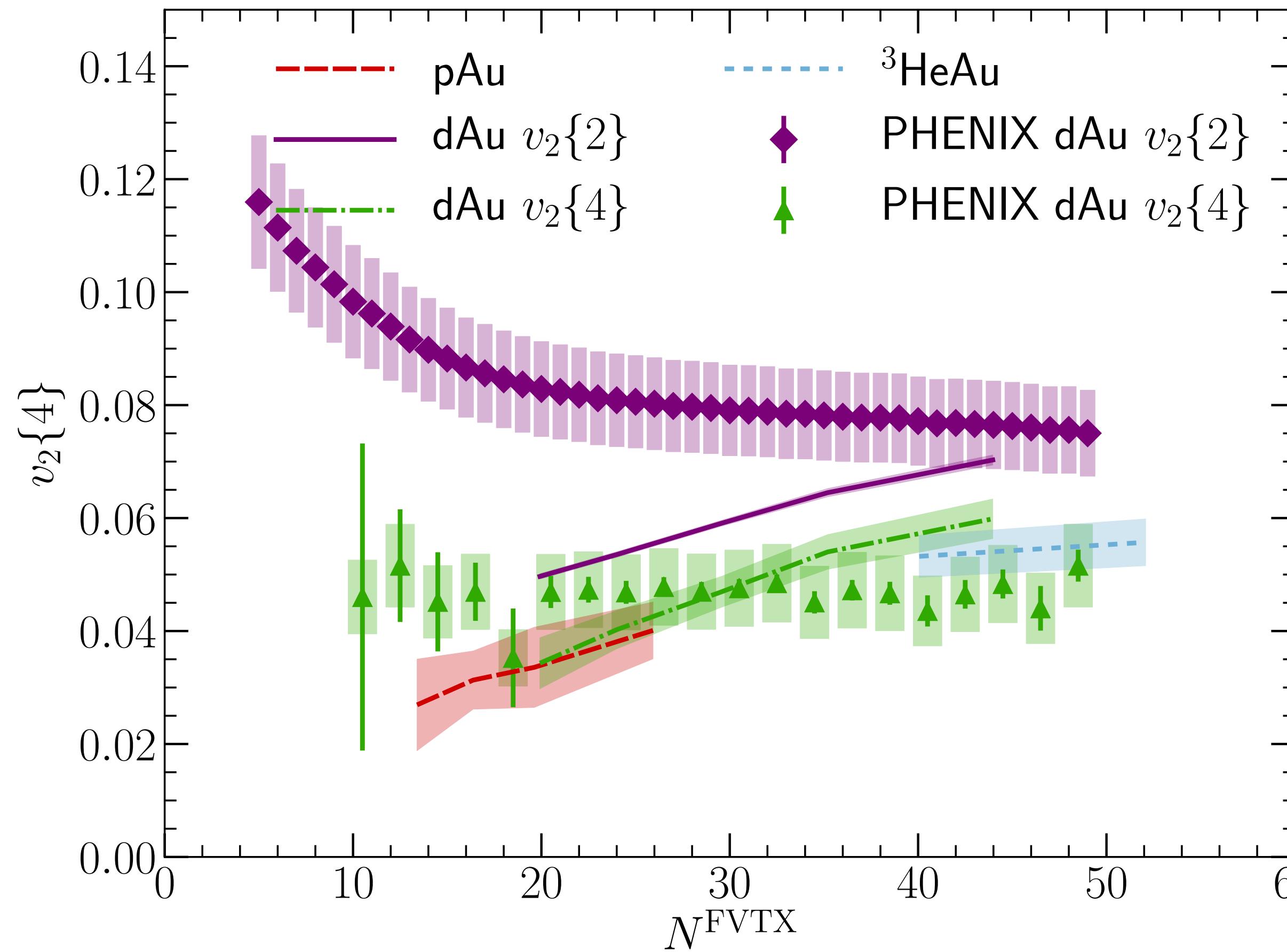


# Small systems: 4-particle correlations

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Schenke, Shen, Tribedy, in preparation

PHENIX Collaboration, Phys. Rev. Lett. 120 (2018) 062302

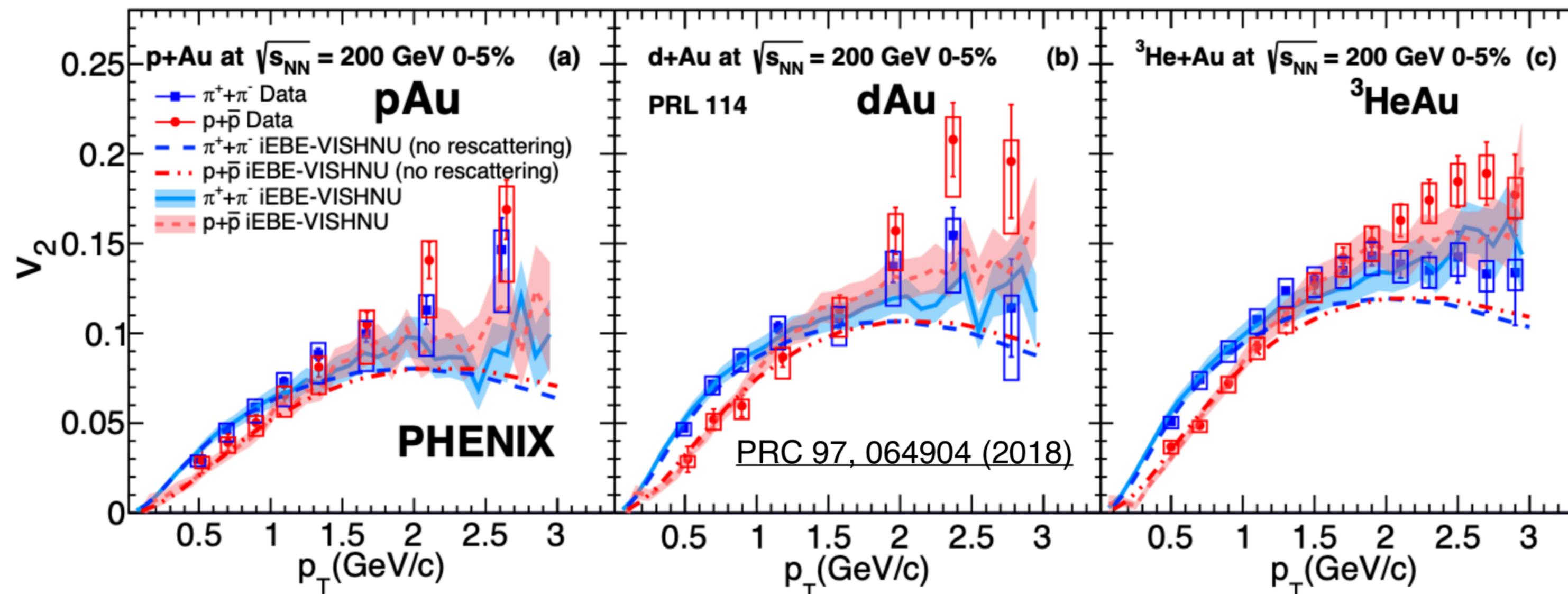


dAu close to PHENIX data but  
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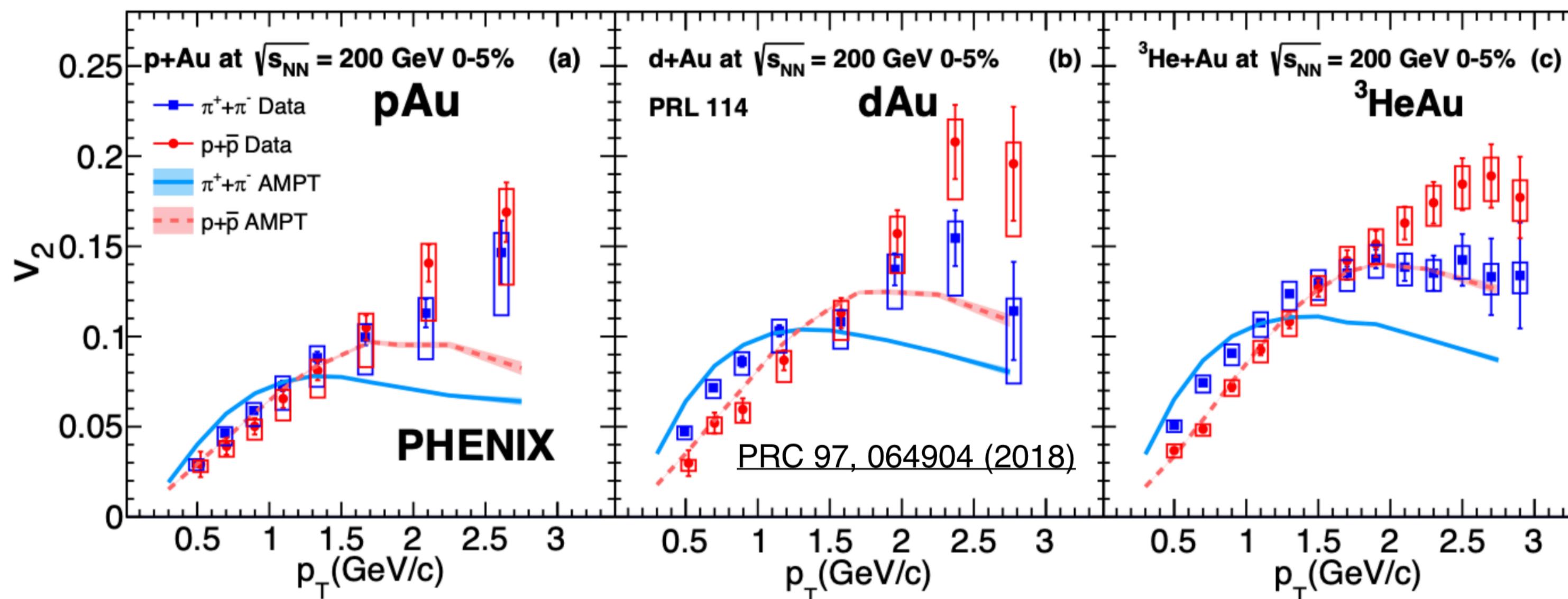
Both pAu and dAu have  
**negative  $c_2\{4\}$**   
unlike PHENIX data

pp needs more statistics

# Mass splitting



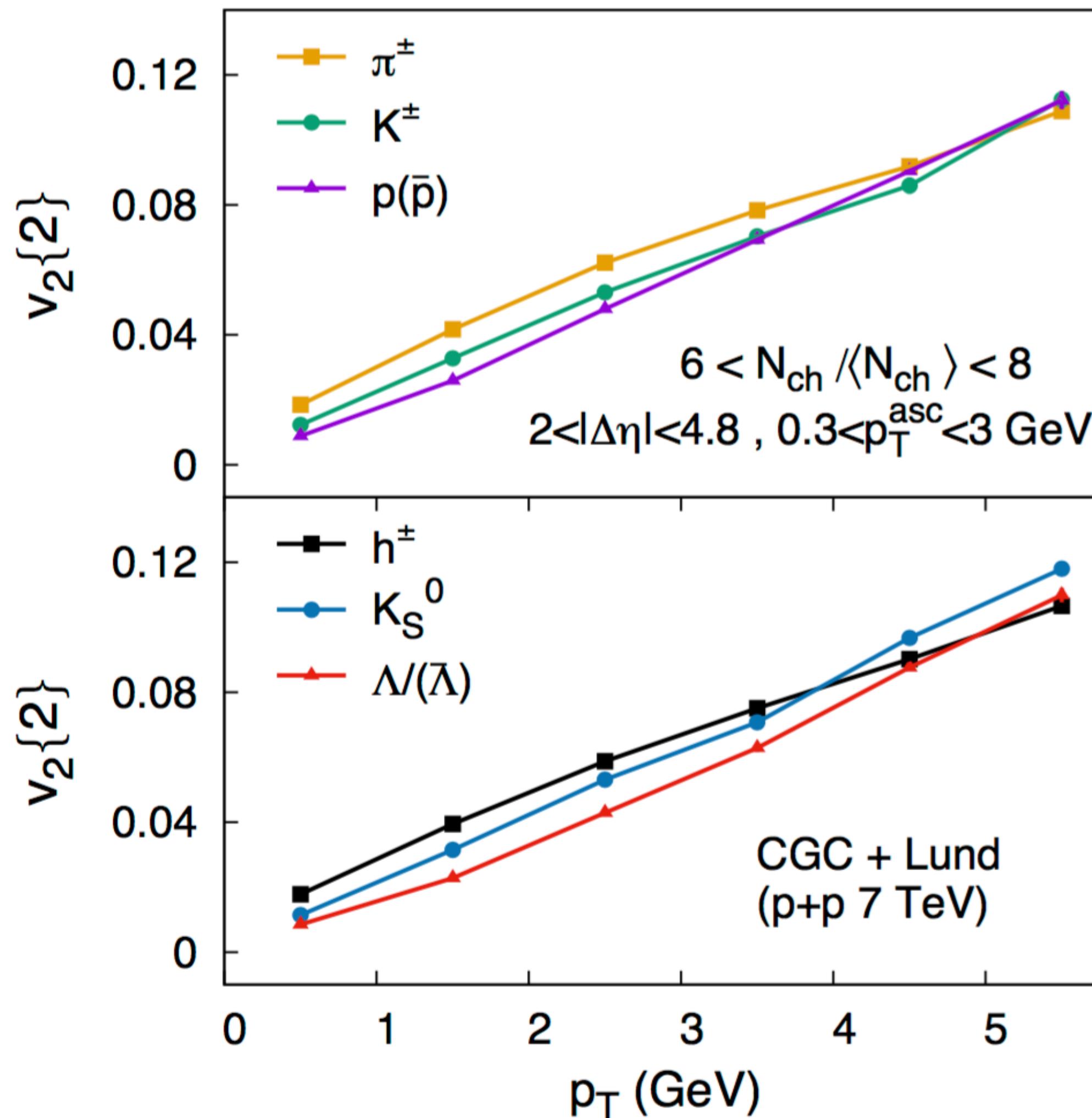
Hydrodynamics reproduces splitting at low  $p_T$



AMPT has splitting at high  $p_T$ ; at low  $p_T$  only when hadronic rescattering included

# Note: Mass splitting without hydro

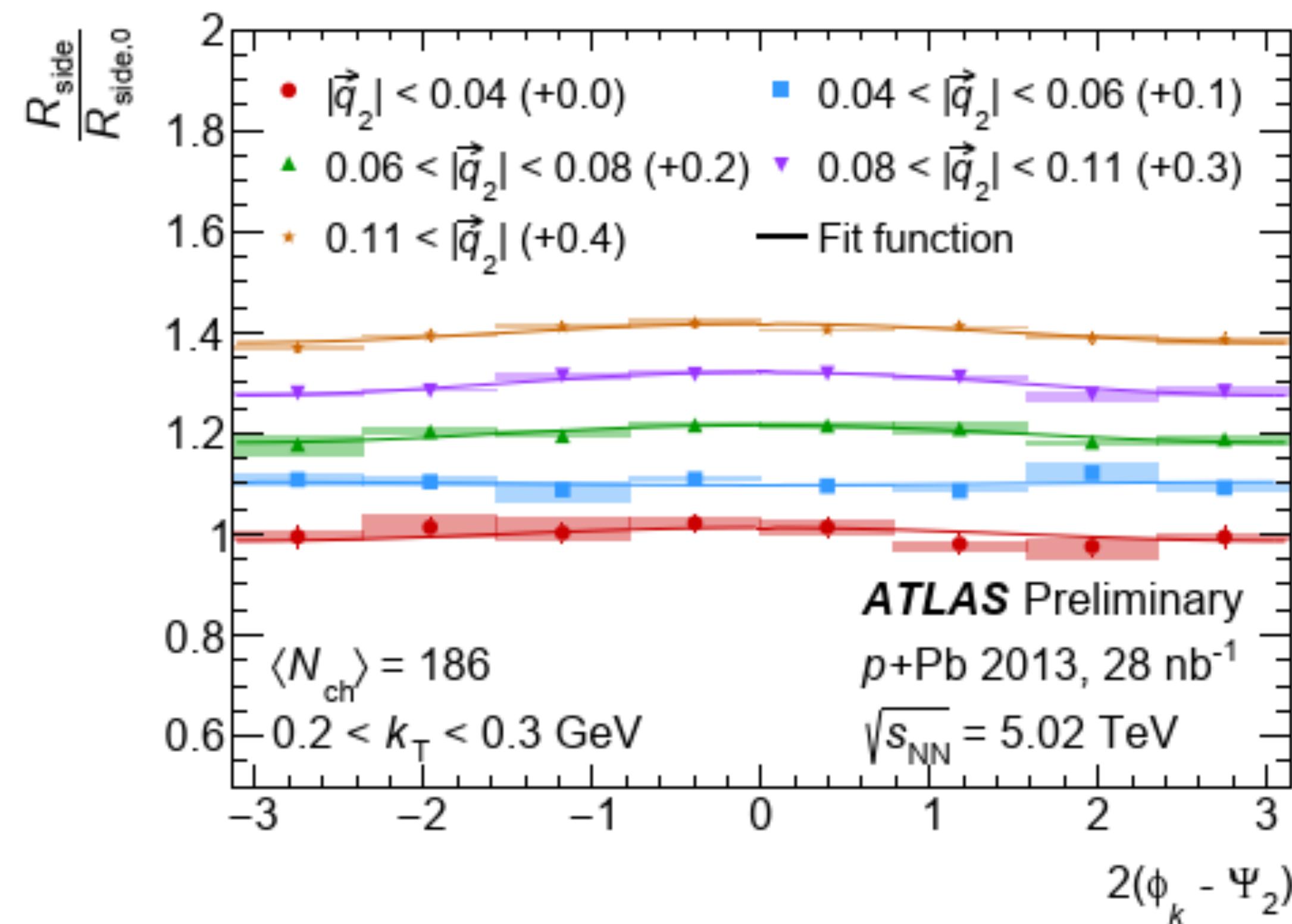
B. Schenke, S. Schlichting, P. Tribedy, R. Venugopalan, Phys. Rev. Lett. 117, 162301 (2016)



Also seen qualitatively in  
CGC + Lund string fragmentation  
where the string gives the common  
boost

Here shown for  $\text{p}+\text{p}$   
Need to do the calculations for  
other systems

# Angle-dependent HBT



More anisotropy of shape of emitting source for events with larger flow anisotropy

Hints at geometry driven flow

# A challenge: Jet quenching

- Conventional Wisdom: Not (non-trivially) modified in pA
- Only quantitative comparison between expectation(theory) and data will tell
- How much jet-quenching / melting would actually be expected ?
- Also weakly bound quarkonia are suppressed (strongly bound ones not)

